Energy at the Frontier:
Low Carbon Energy System Transitions and Innovation in Four Prime Mover Countries

by

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ABSTRACT

All too often, discussion about the imperative to change national energy pathways revolves around long timescales and least cost economics of near-term energy alternatives. While both elements certainly matter, they don't fully reflect what can drive such development trajectories.

This study explores national energy transitions by examining ways in which four prime mover countries of low carbon energy technology shifted away from fossil fuels, following the first global oil crisis of 1973. The research analyzes the role of readiness, sectoral contributions, and adaptive policy in the scale-up and innovations of advanced, alternative energy technologies. Cases of Brazilian biofuels, Danish wind power, French nuclear power and Icelandic geothermal energy are evaluated for a period of four decades. Fundamentally, the research finds that significant change can occur in under 15 years; that technology complexity need not impede change; and that countries of varying governance approaches and consumption levels effectuated such transitions. This research also underscores how low carbon energy technologies may be adopted before they are competitive and then become competitive in the process.

Thesis Supervisor: Professor Lawrence E. Susskind
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INTRODUCTION

The world at large is wrestling with difficult energy choices. There is a strong sense that a way forward must be found to substitute lower carbon energy for traditional fossil fuels (IEA, 2011; G8 and European Energy Commissioner, 2009; World Bank, 2012; undated; United Nations, undated). Nevertheless, no one is entirely clear about how to effectuate such a shift at the national or international scale. The general view is that national energy transitions of any significance take several decades, if not longer, and that cost minimization in the short run is the crucial factor in national energy policy-making. Based on this line of thinking, only energy sources that are cost-competitive have a chance to take hold. While this appears reasonable, it can miss opportunities for wider gains. There are, for instance, a number of countries that have already undertaken significant transformations to low carbon energy, when full cost minimization was not possible at the outset. They not only effectuated major low carbon energy change, but also developed industries around it, often realizing gains in costs, if not full cost competitiveness.

To understand the mechanics of such an endeavor, I chose to study energy system transitions in what I call prime mover countries of low carbon change. Such countries, for the purposes here, are those that have successfully displaced at least 15% of traditional energy sources with a specific type of low carbon energy and increased their use of the same low carbon energy by 100% or more. Although I began with data covering roughly 130 countries, I narrowed quickly to four countries and technologies:

Brazilian biofuels, Danish wind power, French nuclear power and Icelandic geothermal energy. Table 1 outlines the transitions I investigated between 1970 and the present.

Table 1: Market Shares of Low Carbon Energy Studied

Country and Low Carbon Energy	1970	2010
• French nuclear power in electricity	4%	76%
• Icelandic geothermal energy in space heating* • Icelandic geothermal energy in power	43% Negligible	~90% 26%
• Brazilian ethanol in primary automotive fuels	1%	41%
• Danish wind power in electricity	Negligible	20%

*Source: IEA data (2012) for France, Iceland and Denmark; Ministry of Mines and Energy/MME, 2012 for Brazil. *Note: The share of Icelandic geothermal energy for space heating represents the percentage of the population covered, rather than the quantity used.*

Other cases, such as Kenyan geothermal energy and solar thermal energy in equatorial states, hold promise of intriguing empirical insight when conditions allow. German solar photovoltaic power could also be the subject of further research, when a greater substitution level is attained.

I began by looking at the history of energy use in each country, noting technological innovations and adaptations; drivers and barriers as well as the attitudes and involvement of the most important industrial sectors. To benchmark transition performance, I gathered data about the fuel mixes, energy self-sufficiency, levels of industrial development, cost improvements, and evidence of societal acceptance.

The four case studies explore low carbon energy technologies in detail. I also look to determine what pre-conditions for success played a role in each case. Comparing across the cases, three common pre-conditions emerged: a readiness for technological change; the contributions of public actors often amidst cross-sectoral inputs; and the aptness of public policies. In the end, this research challenges some of the conventional wisdom on technological complexity and innovation at a national scale.

Countries can, in fact, alter their energy balance in a significant way -- stressing low carbon energy sources -- in much less time than many decision-makers might imagine. Critical substitution shifts within the transitions that I studied were accomplished often in less than 15 years. Moreover, these transitions were effectuated even amidst circumstances at times involving highly complex energy technologies. At the outset, the majority of the energy sources in this study were not cost competitive, but over time they became so. The four transitions I examined took place in countries with very different energy consumption patterns and styles of governance. So, these aspects do not appear to be major impediments precluding change.

Based on these findings, I echo an aphorism put forward by Jose Goldemberg and his colleagues which indicates that energy, rather than being the destabilizing force that it is today, can become an instrument for achieving a more sustainable world (1988).

STRUCTURE for the STUDY

The remaining sections of this study are structured as follows: Chapter 1 introduces the subject of national energy systems, discussing forces in the current landscape that are shaping choices about energy systems. Chapter 2 outlines the research methodology and approaches employed, as well as the limits of this study. Chapter 3 discusses concepts and theory which underpin the research. Chapters 4 through 7 outline energy system transitions for Brazilian biofuels, Danish wind power, French nuclear power and Icelandic geothermal power. Each case chapter discusses basic technology characteristics and the history of an energy shift, followed by preliminary case analysis of determinants and innovations related to the specific transition. Chapter 8 provides an overview of cross-case analysis, applying a new conceptual framework and taxonomy of energy system change. It then distills the findings with implications for theory and practical application. Chapter 9 concludes with a discussion of policy lessons and areas for future research.

LIMITS

A number of limits are worth noting. First, studies of this nature can benefit from lengthy periods of investigation and defined focus. However, limitations in institutional and individual memories as well as information availability complicate such time spans. Second, in focusing on a small set of cases with select, common traits, one must also exercise care in inferring causality. Finally, practical aspects of the research, including variations in the strength of data and use of translation, also have natural limitations.

Despite these constraints, unanswered questions about the phenomenon of energy system change highlight the need for this kind of study.

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Chapter 1:

Rethinking Energy

If we don't change direction soon, we'll end up where we're heading ....
– Chinese proverb cited by the International Energy Agency, 2011

A. INTRODUCTION

The discovery of oil near Titusville, Pennsylvania in 1859 was a relatively inconspicuous precursor to what would become an epic shift into the modern age of energy (Yergin, 1991 and 2011; Giebelhaus, 2004).[1] At the time, the search for 'rock oil' was spurred by a perceived shortage of lighting fuel (Ibid). Technology advances in petrochemical refining and internal combustion engines had yet to occur, and oil was more expensive than coal (Ibid, Flavin, 2008; Grubler, 2004). Nevertheless, in less than a hundred years, oil gained worldwide prominence as an energy source and traded commodity (Ibid). Today, global consumption of oil equals roughly 88 million barrels per day, accounting for approximately 33% of the global primary energy supply (BP, 2012).[2]

Along similar lines, electricity in the early 1900s powered less than 10% of homes in the United States (Flavin, 2008). Yet in under a half a century, billions of homes around the

[1] The 'discovery' of oil or petroleum is employed loosely. Prior to 3,000 B.C., recorded history indicates that oil was used as asphaltic bitumen in Mesopotamia (Giebelhaus, 2004). Later adaptations included its use in water-proofing of ships and in construction, in addition to applications in medicine, illumination, and incendiary devices (Ibid). At the time of the Titusville discovery, other developments related to petroleum were already underway in Azerbaijan and France (Smil, 2010).

[2] The share of total primary energy derived from oil has decreased from 48% in 1970 (BP, 2012).

world were equipped to utilize this refined form of energy (Ibid; Hughes, 1983 and 1990; Nye, 1992). Estimates indicate that roughly 75-80% of the world's population now has access to electricity (Gronewold, 2009; Ki-moon, 2011). For both petroleum and electricity, significant shifts in energy use and associated technologies were closely tied to evolutions in infrastructure, institutions, investment and practices (Cleveland, 2009; ; Giebelhaus, 2004; Grubler, 2004; Hughes, 1983; Nye, 2009; Smil, 2010; Yergin, 1991).

Questions about the security of energy supplies, environmental effects, and fuel price volatility have led many to more fully weigh non-fossil fuel based options as a strategy going forward.[3] Challenges to the durability and quality of the existing natural system from current forms of energy utilization make it increasingly clear that adaptations at the national and global scale are needed. Adopting an energy strategy with low carbon energy, like renewable energy or nuclear energy, may be necessary to mitigate ecological impacts of energy use, while strengthening energy self-sufficiency and reducing the effects of price fluctuations and geopolitics (IEA, 2011; UNDP et al, 2000; Intergovernmental Panel on Climate Change/IPCC, 2007 and 2011). If done well, a low carbon energy approach could serve to not only reduce many ecological risks, but also produce economic benefits, enhance national security, and meet basic societal needs

[3] See Goldemberg et al, 1998; Holdren, 2006; International Energy Agency/IEA, 2010b; Lovins, 1976; United Nations Development Program/UNDP et al, 2004; United States Department of Energy/US DOE, 2011a; Ki Moon, 2011; Sustainable Energy for All, 2011.

(Ibid; Olz et al, 2007; President's Council of Advisors on Science and Technology/PCAST, 2010; UNDP et al, 2000).[4]

Numerous countries have the opportunity to shift to more sustainable energy pathways.[5] Examining the conversion dynamics of a number of prime mover countries in low carbon energy can provide lessons and insights for decision-makers in countries now seeking to alter their energy balances.

Brazil, Denmark, France and Iceland have realized substantial benefits to date by shifting to renewables or nuclear energy in their power, heating and/or transport sectors. Brazil, for example, has transformed a portion of its transport and agricultural sectors with biofuels production and related technologies (Chapter 4). It is now partnering internationally as a leader in biofuels research and development, and technology diffusion, in addition to its work to create an international biofuels commodities market. France and Denmark adopted considerable shares of nuclear and wind energy,

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[4] A recent study by McKinsey & Company indicated that adoption of a low carbon energy strategy, in addition to energy efficiency measures, could provide roughly 70% of the global electricity supply in 2030 compared to 30% in 2005 (2009). Similarly, increased substitution of biofuels for conventional transport fuels could provide up to 25% of global transport fuel by 2030 (Ibid). Combined with other low carbon approaches, this strategy is estimated to produce savings of roughly 12 $GtCO_2$ (Gigatons of carbon dioxide) per year in 2030 (Ibid).

Note: McKinsey & Company's analysis for the power sector includes measures like hydropower and carbon capture and sequestration which go beyond the scope and definitional bounds of this study (Ibid).

[5] See World Energy Council/WEC, 2010a and 2010b; National Renewable Energy Laboratory/NREL, 2004; Renewable Energy Network/REN21 2010; People's Daily/PD, 2010; World Bank 2009; World Bank et al, 2010; Johnson et al, 2009.

respectively, in their power sectors (Chapters 6 and 5). Industrial development in these energy technologies has positioned the two countries as international market leaders in these fields. Iceland has integrated significant shares of geothermal energy into its power and heating sectors (Chapter 7). It is a historical leader in geothermal development, serves as an international hub for training on geothermal energy technology, and became a model for industrial spillovers in the process.

Drawing upon the above cases, the current study aims to critically analyze energy transitions. The reason is simple. There are many now seeking to reduce reliance on fossil fuels, while optimizing domestic resources and technological abilities. This research can inform such choices. The rest of this chapter covers the following:

- Basics of an Energy System
- Energy Outlook
- A Closer Look at Fossil Fuels
- Altering the Playing Field with Fuel-switching
- Barriers to Change
- Research Questions

B. BASICS of an ENERGY SYSTEM

To understand major transitions in national energy systems, it's useful to first consider the fundamentals of an energy system.[6] An energy system consists of inputs, outputs, and actors (including institutions) involved in processes of energy exploration, production, transformation, delivery, and use within an enabling environment. Whether the system is national in form, international or sub-national, natural resources serve as primary inputs that are converted and then utilized with various applications and technologies.

Types of Energy

Primary energy is the type of energy that is embodied in natural resources like fossil fuels; elements, like uranium; and renewable energy (Smil, 2010, 2007 and 1991; Amaroli and Balzani, 2011; Goldemberg and Lucon, 2010; Verbruggen et al, 2011). It differs from final energy in that the former is mostly unrefined when it enters the energy system, whereas the latter is what is consumed after processing, transformation and distribution (Ibid).

Looking more closely at the kinds of primary energy feedstock, fossil fuels include coal, natural gas and oil – each of which is converted for energy use, primarily through combustion (Ibid). Elements including uranium, plutonium and thorium (various

[6] System can be defined differently in various fields (Pidwirny, 2006; Buckley, 1976; Wilson, 1980). Here, it refers to elements or inter-related components within a set structure, involving certain behavior, interconnectivity, stocks and flows. Predictability is inherent in some definitions, yet is not implied or required for this discussion of energy systems.

isotopes, in some cases) generate nuclear energy through fission or fusion processes (Chapter 6). Renewable energy consists of a range of energy sources – namely, hydro, ocean and wave energy, geothermal, wind, and solar energy (Ibid). Among the renewable sources (used interchangeably, here, with renewable energy technologies/RETs), energy is derived essentially from solar radiation or the Earth's heat (Ibid). The energy source that is utilized with RETs generally replenishes, so it can be thought of as an energy flow. This contrasts with fossil fuels and feedstock for nuclear energy which are exhaustible stocks.

Key Decision-makers

Within an energy system, principal decision-makers, of course, can include energy producers, distributors and end-users as well as policymakers/regulators and innovators. Frequently, government is a major player in the provision of energy services, since energy is widely accepted to be a basic human need that cannot be sufficiently met by standard markets (UNDP et al, 2000).[7] When engages in energy services, government may do this indirectly as a regulator or directly as a supplier. Industry generally includes a fairly predictable set of actors -- namely producers, distributors, and researchers. Civil society broadly encompasses the end-users.

[7] Open markets are designed to generally align supply and demand, so do not by nature prioritize public goods like energy security, public health or a clean environment. Markets also do not typically account for distortions, such as information asymmetries, which are covered in greater depth later.

Supply and Demand

When contemplating the dynamics of energy supply and demand, the level of competition and regulation in a given system's market will factor importantly. Yet at an even more basic level, are a few commonly-shared factors. On the supply side, the adequacy of feedstock, potential return on investment and risk/uncertainty encompass typical determinants (Dahl, 2004; Yergin, 1991 and 2011). These, in turn, are influenced by prices, the accuracy of knowledge or information, the presence of infrastructure and energy substitutes, and policy regimes (Ibid; IEA, 2011 and 2010c). On the demand side, prices and access to energy factor largely (Ibid). Within the sphere of access, infrastructure and end-user technology are instrumental (Grubler, 2004; Jones, C., 2009; Patterson, 2005). Interestingly, the quality of energy is increasingly found to be important for demand, as people are seeking more convenience, flexibility, efficiency, and environmentally clean energy accompanying increases in income per capita (Nakicenovic et al, 1998).

Turning next to markets, there is at least one mechanism to align energy supply and demand within an energy system. This is based principally on trading or price-setting. At the country level, multiple markets typically operate by sector (heating, electricity and transport) and/or region. With trends in liberalization and globalization altering the contemporary playing field, even larger markets exist. [8] It's not uncommon for national

[8] Liberalization refers to the introduction of competition into formerly monopolistic conditions (Public-Private Infrastructure Advisory Facility/PPIAF et al, 2011). For a discussion of principal drivers and elements of such reform, see Bacon and Besant-Jones (2001). Globalization refers to the increasing interconnectedness of the global economy concurrent with the diffusion of ideas across national borders.

and regional energy markets to be impacted by international developments in far-reaching regions in today's environment (Yergin, 2011).

Focusing on energy investment, a number of distinctions emerge for supply and demand-side technology. On the demand-side, turnover of energy end-use technology is fairly frequent and covers large quantities, so can be characterized as happening at scale. In the American transport sector, for example, roughly 12 million lightweight vehicles have been purchased on an annual basis, until recent times (Koonin and Gopstein, 2011), with such vehicles expected to last 5-15 years. This level of turnover provides significant opportunities to learn, to optimize infrastructure, and to readily diffuse advances (Ibid). By contrast, supply-side technology is purchased with the expectation that it will produce returns on investment, lasting for decades. Nuclear plants, for example, were originally expected to be in service for 25-40 years and are now undergoing retrofits and new designs to last for 60+ years (World Nuclear Association/WNA, 2011a; Interviews, 2011-2012). For supply-side decision-making with such long-held assets, opportunities still exist to adapt processes, technology and infrastructure, but change occurs at a much slower pace.

Distinctions between supply and demand conditions generally translate into different kinds of policy approaches. Energy supply-side policies, for example, often center on research and development (R&D) spending and investment tax write-offs for capital expenditure, whereas energy demand-side policies have frequently included procurement programs and portfolio standards (Sawin, 2001; Grubler et al, forthcoming).

C. ENERGY OUTLOOK

Global primary energy use is intensifying along an uncertain path. In 2010, it equaled 558 Exajoules/EJ, more than 20 times that in 1850 (Table C1). Of the total energy now used, more than 80% is derived from fossil fuels (BP, 2012). If current policies remain in place, the IEA estimates there will be a roughly 50% increase in global demand for energy by 2035 (2011).[9] Accompanying this growth, fossil fuel use is expected to rise also by about 50% (Ibid), yet the viability of this path is brought into question by geopolitical challenges, economic risks, and ecological impacts, among other issues.

Table C1:
Global Primary Energy Estimates (EJ)

1850	25
1900	45
1950	100
2000	450
2010	558

Source: Adapted from Holdren, 2007 and Communications with Holdren, 2011. See also Figure D1.

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[9] Consumption per capita of commercial energy** in the developing world is less than 20% that of the industrialized world, nonetheless developing country populations are expected to increase by a factor of 10 within two generations (UNDP et al, 2004). Currently, about 20% of the world population does not have access to reliable energy (Herron, 2011; IEA, 2011).

**Note: Commercial energy, as it is used here, refers to fossil fuels (oil, coal, and natural gas), nuclear energy, and large-scale hydropower. It does not reflect new renewables - modern biofuels, wind, solar, small-scale hydropower, marine, and geothermal energy – or locally collected and often unprocessed biomass-based fuels, such as crop residues, wood, and animal dung (UNDP et al, 2000).

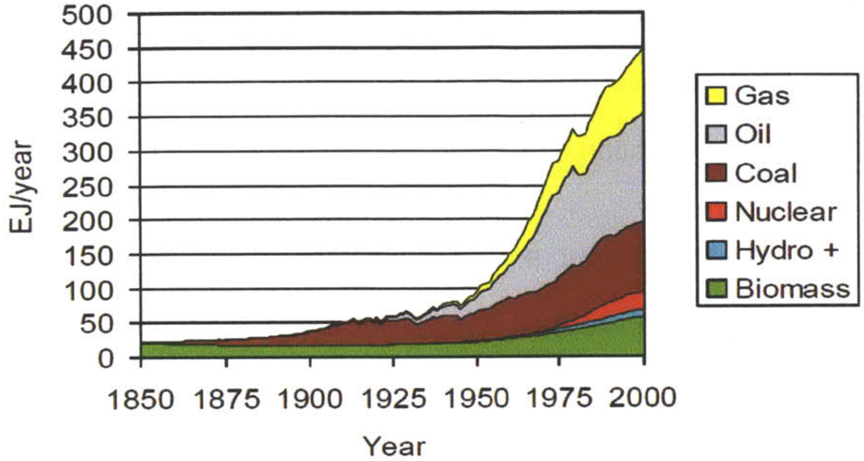
As of the end of 2011, proven fossil fuel reserves and existing production rates (P/R) indicated there is a global supply availability of 54 years for petroleum, 64 years of natural gas and 112 years for coal (BP, 2012).[10] This indicator serves as a simplified gauge with differences naturally existing across regions and countries. However, over the longer term, production costs can be expected to rise as known reserves diminish and more costly technologies are utilized to explore and extract less feasible forms of the resources (Tanaka, 2009a).

D. A CLOSER LOOK at FOSSIL FUELS

Since the mid-1800s, absolute and relative usage of fossil fuels has increased, implying that there is growth not only in the unit quantity, but also the share of this form of energy compared to other fuel types utilized in the energy mix (Figure D1).

[10] Proven reserves are those deemed technically and economically feasible to recover.

Figure D1: World Primary Energy Consumption 1850-2000



Source: Holdren, 2007. Note: Units are Exajoules per year. Hydro+ consists of hydropower, geothermal energy, wind power, and solar energy. Fossil fuel contributions are calculated at a higher heat value to include fuel energy in the heat of vaporization of combustion-produced water, which would be excluded with a lower heat value calculation. The hydropower contribution is calculated based on energy content (3.6 MJ/kWh), rather than fossil-fuel equivalence (~10 MJ/kWh) (Ibid; Holdren, 2008; Communications with Holdren, 2011-2012).

The more than 150-fold increase in global fossil fuel consumption (BP, 2011) is often credited to gains with the fuel density, portability, and costs relative to other options (Grubler, 2004).[11] However, major changes have also occurred in the enabling environment since the 1850s, including the introduction of new technologies and energy entrants which have altered the energy playing field. Nuclear energy, for instance, emerged formally as a source of electricity in the 1950s.[12] Refinements in technology

[11] Historical reporting of commercial energy use by BP indicates that fossil fuel consumption in 1850 principally involved coal equaling 53.7 Mtoe (2.25 EJ) (2011).

[12] Electricity was first derived from nuclear power at the National Reactor Testing Station in Arco, Idaho in 1951 (International Atomic Energy Agency/IAEA, 2004). In 1954, the Obrinsk Nuclear Power Plant based in the former Soviet Union became the first nuclear power plant to generate grid-connected electricity, producing roughly 5 megawatts/MW of electric power (Ibid; Chapter 6).

modularity and delivery have also produced new opportunities for energy transport and access. Hybrid solar-wind generators, for example, can be deployed as large-scale clusters of generation units or used in smaller numbers as stand-alone sources of energy in remote areas without grid connection (US DOE, 2011b).

In numerous cases, fossil fuels did not begin with a clear advantage (Jones, C., 2009; Flavin, 2008). The introduction of new technologies; infrastructure, like canals and pipelines; as well as eventual gains from economies of scale facilitated widespread use of fossil fuels (Ibid; Grubler, 2004; Yergin, 1991).[13] As with any energy choice, the scale-up of such energy utilization has not been without consequences. Complexities associated with import dependence, supply security, ecological and public health effects, as well as embedded subsidies are covered next.

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[13] Economy of scale, here, refers to cost advantages gained through (1) expansion/ increased production of units or (2) optimization of a power plant size.

Imports of Fossil Fuels

Global trade in fossil fuels has undergone considerable change in recent decades. In terms of pure volume, fossil fuel imports increased worldwide by about 170% since the early 1970s.[14]

If considered with respect to the dollar value of imports traded in a given year, fossil fuels increased from 10% of global imports in 1970 to 15% in 2010 -- currently equaling $2 trillion (Table D1).[15] Of the $14.0 trillion in total imported commodities worldwide for 2010, petroleum and petroleum products alone equaled $1.7 trillion or 12%, ranking second overall behind electrical machinery, apparatus and appliances (UN Comtrade, 2011).

Table D1: Fossil Fuel Imports as a % of Total World Imports

1970	10%
1980	25%
1990	11%
2000	10%
2010	15%

Source: United Nations Conference on Trade and Development/UN Comtrade, 2011.

[14] Total imports of fossil fuels rose from 74.4 EJ in 1971 to 201.2 in 2010 (IEA, 2012). Of total energy imports, 99.6% were fossil fuels in 1971 and 98.7% were that in 2010. The latter statistic reflects little change in relative shares, as electricity imports have increased from <1 to 1.1% of total global energy imports between 1971 and 2010 (IEA, 2012).

[15] Petroleum, gas and coal products are classified here under SITC Rev 1 (UN Comtrade, 2011).

The magnitude of fossil fuel trade may be considered a sign of its favorable trading status. However, this also represents transferred revenue or wealth, which arguably provides energy export countries with strategic leverage over energy import countries (Levi, 2010). Table D2 shows import costs and shares of imports for select countries or regions in 2010. Of these, the United States spent the most in quantity terms at nearly $1 trillion in 2010, whereas Japan and India ranked as some of the highest for fossil fuels as a share of their total import costs. For energy importing countries, energy dependence can have varying consequences for freedom of action in foreign policy (Holdren, 2006a). It may, for example, lead energy importers to adopt a more conciliatory policy stance toward energy exporters than would otherwise be the case. This reliance can also directly translate into less indigenous support for domestic business, employment and social development (UNDP et al, 2000).

Table D2: Fossil Fuel Imports – Select Countries/Regions (2010)

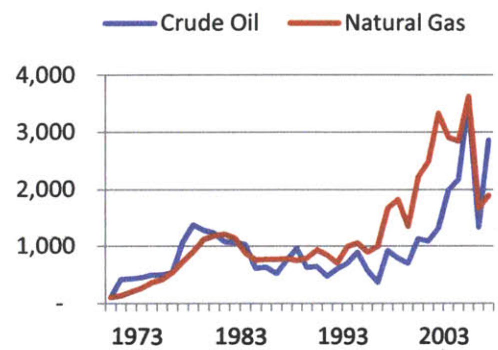
	Share	**Amount**
China	13%	$187 B
EU-27	23%	$456 B
India	35%	$ 83 B
Japan	29%	$198 B
United States	18%	$986 B

Source: UN Comtrade, 2011.

Figures D2 and D3 show recent, international price trends for petroleum, natural gas and coal. Significant price spikes may be seen across all three fuels types since 2003. When such increases occur in international energy prices, energy importing nations risk sharp deficits in their trade balances. For petroleum alone, the IEA projects that prices (currently trading at roughly $105-128 per barrel) may reach $200/barrel by 2030 due to rising demand pressures and resources limits (EIA, 2012; IEA, 2010a; Bloomberg, 2011a).

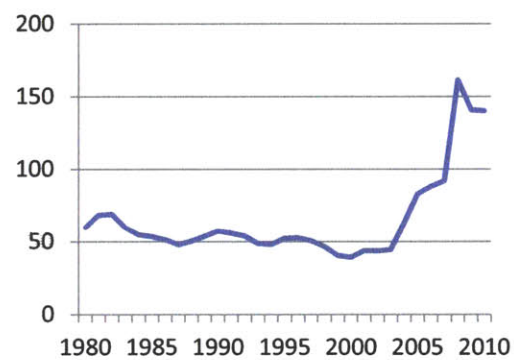
Figures D2 and D3: Energy Price Flux

Petroleum and Gas Prices,
(Nominal $, Indexed by fuel, Base year 1973 = 100



Source: Data adapted from the Energy Information Administration/EIA, 2011, Tables 9.11 and 11.7, natural gas price is at the wellhead and petroleum prices are an average of international prices.

Average Coal Import Prices
($ per Tonne for the EU and Japan)



Source: IEA data, 2011, Steam and coking coal are combined.

The links between global economic activity and energy price volatility are fairly well-recognized. A $10 increase in the price of oil per barrel, for example, will slow the global economy by 0.5% per year (UNDP et al, 2004). A roughly $100 increase per barrel relative to current prices -- not unheard of in recent times -- could bring a notable slow-down of 5% with concomitant uncertainty for economies.[16] By comparison, the 'worst period' (defined in simple economic terms) of the ongoing, global economic downturn

[16] Related analysis by McKinsey & Company, estimates that global growth would slow 0.6-0.9% in the first year, if crude oil prices were to remain around $125 or $150 per barrel for an extended period of time (2011).

was measured with the 5.4% slow-down in economic growth between 2008 and 2009 (World Bank, 2011).

Security of Supply

The security of supply is another consideration with respect to fossil fuels.[17] Security, for the purposes here, refers to the availability of energy in sufficient quantity, at affordable prices and without unacceptable or irreversible harm to the environment (UNDP et al, 2004). Commonly recognized challenges to the physical supply of energy can arise from human error, attacks on the system or sources, political or cartel activity, natural disasters, and incapacity of the infrastructure to deliver. Currently, the global spare capacity of oil and natural gas is said to be tight due to recent energy trends in increased demand and a reduction of excess capacity (EIA, 2011; Yergin, 2011; Energy Research Institute, 2011; Janssens et al, 2011). This means that the provision of oil and natural gas, comprising 57% of primary energy consumption in 2011, has limited flexibility for shortfalls or disruptions (Ibid; BP, 2012; Tanaka, 2009a). Examples of recent supply weakening are evident in oil supply disruptions in Libya; gas supply disruptions to the Ukraine; pipeline bombings in Nigeria; hurricane destruction of oil rigs in the Gulf of Mexico; and oil tanker hijackings off the coast of Somalia (IEA, 2010a and 2011; Bloomberg, 2011b).[18]

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[17] Energy security applies to all forms of energy. However, this section focuses principally on fossil fuel-related characteristics.

[18] Energy security risks also exist with domestically-sourced energy and may be linked to complex energy systems. For a discussion, see Lovins and Lovins, 1982/2001.

Arguably, one of the most persistent forms of supply insecurity with fossil fuels is instability in supplier regions. Table D3 shows the top 6 export regions for oil in 2011, representing 92% of global oil exports. In the past decade, at least half of these oil export regions evidenced political unrest, resource nationalism or deliberate forms of supply disruption.[19]

Table D3: Crude Oil Exports by Region (2011)

Export Region	Oil Exports as a % of Total World Oil Exports
▪ Middle East	36.2
▪ Former Soviet Union	15.9
▪ North America	12.5
▪ Asia Pacific*	11.4
▪ West Africa	8.5
▪ South and Central America	6.9

*Source: BP, 2012. *Excludes Japan.*

Figure D4 provides another view of energy suppliers, namely the top oil and gas companies, based on ownership of oil and gas reserves. These companies are located

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Note: Supply weakening can also occur with low carbon energy, as with that seen in the Fukushima nuclear meltdown in Japan in March 2011.

[19] During the Arab Spring, revolutions and other major political uprisings occurred in countries of North and West Africa as well as the Middle East.

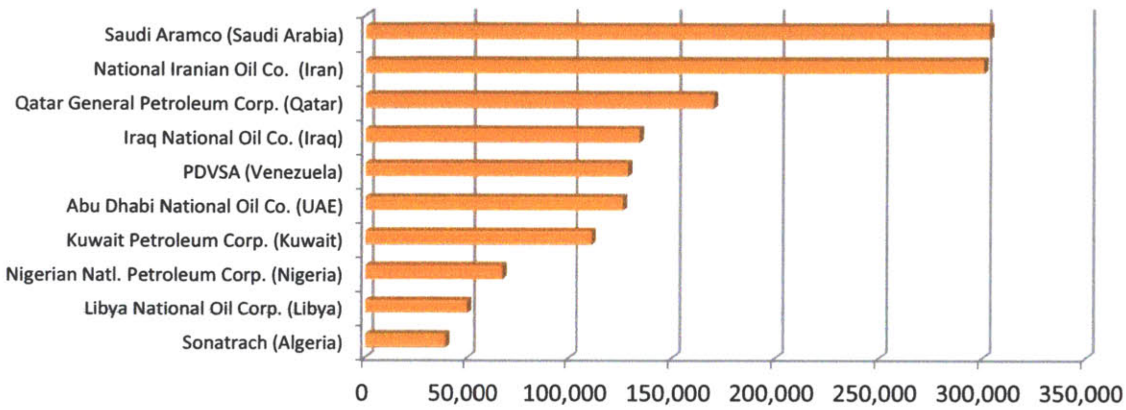
Russia has history of natural gas disputes with neighboring countries leading to delivery disruptions. A dispute in January 2009 with Ukraine led to supply disruption in 18 other countries (Jones, R., 2008; Reuters, 2009).

Resource nationalism or expropriation of oil and/or gas fields by the state was evident in Venezuela, Bolivia, Ecuador and Russia (British Broadcasting Company/BBC, 2006; Ingham, 2007; Johnson, T., 2007; McAllister, 2007; Olson, P., 2006). Cases, particularly in Russia and Ecuador, occurred allegedly on the basis of contractual differences.

Top natural gas exporters are Russia, Norway, Canada, Algeria and Qatar (Central Intelligence Agency/CIA Factbook, 2011).

in countries where resource nationalism, supply disruptions and/or recent unrest have occurred in recent years.[20]

Figure D4: World's Largest Oil and Gas Companies Based on Oil Equivalent Reserves of Liquids and Natural Gas *(Million Barrels of Oil Equivalent/MBOE)*



Source: Adapted from Petrostrategies, as of July 18, 2012. All are OPEC member states.

A point worth underscoring is that the world's largest oil and gas companies are principally state-owned. This generally means that, by institutional design or function, their industrial aims are more closely in alignment with the preferences of their national governments (Marcel, 2005; McPherson, 2003; Stevens, 2003; United Nations Centre for Natural Resources, Energy and Transport/UNCRET, 1980). Such association between an energy supplier and a national government can produce valued, societal benefits, as in ensuring affordable energy services for citizens. However, these ties can also influence exports of energy or business plans, if the political agenda of a government or political unrest redefines a state-owned energy company's aims.

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[20] This point must be kept in context, since signs of instability were evident in practically every corner of the globe in 2011 with high unemployment, bankruptcies, foreclosures and sovereign debt crises linked to the current, global economic downturn.

When discussing energy supply stability, the costs of safeguarding supply routes and of fostering such stability are often not part of the standard, public calculus. Research, for instance, on military costs associated with foreign oil for the Unites States range from $5.6 to 14.6 trillion for the period 1970 to 2004 (Sovacool and Brown, 2010, citing Delucchi and Murphy, 2008, and Greene and Ahmad, 2005). This, of course, does not encompass the full costs of the military engagement in Iraq over the last decade. Compared to the American economy that was estimated to be $14.7 trillion in 2010 (ppp) (Central Intelligence Agency/CIA, 2011), the military costs of assuring access to foreign oil can naturally be quite substantial. Some point out that maintaining a military presence at substantial cost in an unstable energy export region may be justified for more reasons than simply supply security (Levi, 2010). Nonetheless, the cost of securing shipping routes is generally never reflected at the gasoline pump.

Ecological Effects and Public Health Considerations

Another area where fossil fuel use has important consequences is in its impacts on the natural and societal environments. In ecological terms, fossil fuel use is linked to the degradation of water, air and land quality through spills, contamination, emissions and extraction practices. Specific to public health, effects of fossil fuel extraction and use are associated with respiratory disease, rheumatic disorders, cancers, and premature fatalities (Baumuller et al, 2011; Goldemberg and Lucon, 2010; Argo, 2001; UNDP et al, 2004).

Focusing on one particular dimension of the natural environment — that of air quality, research indicates that emissions from fossil fuel combustion are linked to urban air pollution that is thought to be responsible for roughly 800,000 deaths per year worldwide (UNDP et al, 2004).[21] Regionally, fossil fuel emissions produce precursors of acid deposition which can disperse thousands of kilometers within and across borders to damage harvests, natural systems, and anthropogenic structures (Ibid; Goldemberg, 2006; Goldemberg and Lucon, 2010; Shah, et al, 2000). At a global scale, use of fossil fuels reportedly contributes about 57% of total greenhouse gases which are changing the composition of the atmosphere and the climate system (UNDP et al, 2004; IPCC, 2007) (Box D1).

Environmental consequences of fossil fuel use manifest in other ways. Oil spills and gas flaring, for instance, can lead to the collapse of local fishing and farming and/or the loss of habitat and biodiversity (Baumuller et al, 2011). Leakage and runoff of pollutants from coal mining or natural gas hydraulic fracturing can compromise soil and water aquifers (Environmental Protection Agency/EPA, 2011a and 2011b; Osbourne et al, 2011).[22] Additional stresses to the environment may be seen in Appendix, Table A1.

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[21] Fossil fuel emissions include particulate matter, sulfur dioxides, nitrogen oxides, volatile organic compounds, carbon monoxide and carbon dioxide, among other pollutants.

[22] The extent to which hydraulic fracturing pollutes water aquifers remains under debate and study (Macallister, 2011; Urbina, 2011a and 2011b; Massachusetts Institute of Technology/MIT, 2011; Stevens, 2010).

Fundamentally, quantifying the cost of fossil fuel use to the ecological system and to public health is difficult to accomplish because there are significant limits to data.

Box D1: Greenhouse Gas Emissions

Greenhouse gas (GHG) emissions are increasingly recognized as primary determinants behind the radiative forcing of the atmosphere that is producing climate change (IPCC, 2007). Atmospheric concentrations of CO_2, a principal indicator of GHGs, have risen from 280 parts per million/ppm in 1800 to 393 ppm, as of January 2012 (monthly mean) (Ibid; NOAA, 2012). Should trends continue, the CO_2 level is expected to rise substantially by 2100 with more extreme weather events and an increase of 2-4 degrees Celsius in the average global surface temperature (IPCC, 2000 and 2007). A more near-term, business-as-usual estimate indicates the GHG from energy will rise 45% by 2030 (Tanaka, 2009b).

The below table indicates GHG emission intensities on a per kilowatt hour (kWh) basis. Here, renewables and nuclear power have the lowest possible intensities and fossil fuel have the highest, differing in many cases by multiple orders of magnitude.

Lifecycle Analysis of GHG Emissions for Select Fuels (g CO_2 equiv per kWh)

Coal	Oil	Gas	Nuclear	Wind	Hydro-power	Geo-thermal	Solar	Biomass
675-1689	510-1170	290-930	1-220	2-81	0-43	6-79	5-217	(633)-75

Based on a literature review of lifecycle analyses for GHG emissions of power generation technologies (Moomaw et al, 2011).

Moreover, people differ on how to value human life and the environment (Costanza and Ruth, 1998; Doran, 2001; Law, 2005). One recent attempt to estimate such costs in the United States valued health impacts at $120 billion per year for premature deaths associated with air pollution (National Academy of Science, 2010). Of the estimated 20,000 deaths per year cited in the study, the majority was attributed to fossil fuel emissions from power plants and vehicles. In terms of environmental damage from gasoline and diesel fuel costs, estimates pinpointed additional costs of $0.23-0.38 per gallon above what would ordinarily be paid at the gasoline pump (Ibid).[23]

Subsidies for Fossil Fuel Use

An area of under-acknowledged significance in the energy sphere, at times, is the extent to which fossil fuels are subsidized. Energy subsidies are a form of economic aid to a producer or consumer, often used with new technology to stimulate production or consumption of a particular form of energy (United Nations Environment Programme/UNEP, 2008).[24] In recent years, global subsidies supporting fossil fuels have averaged $426 billion per year, according to the International Energy Agency (2010a and 2011).[25] By comparison, global subsidies for renewables were $66 billion in 2010 (IEA, 2011). A related estimate by the Bloomberg New Energy Finance indicated that fossil fuels received subsidies nearly 13 times more than renewables in the period 2008-2010 (Energy and Environmental Management/EAEM, 2011). By subsidizing fossil fuels, often said to be the 'least cost fuel', prices are distorted, limiting consumers' capacity to adequately judge scarcity and other considerations. It is worth underscoring that fossil fuels are not new entrants to the energy landscape and some have been

[23] This does not cover effects of climate change, pollution control devices or oil combustion specific to travel by rail, sea and air (National Academy of Science, 2010).

[24] For a discussion of subsidies, see Koplow and Dernbach (2001).

[25] Subsidies for fossil fuels in 2008 equaled $558 billion, $312 billion in 2009, and $409 billion in 2010. Variation is due to international price flux, domestic pricing policy and demand trends, among drivers (IEA, 2010a and 2011).

supported for significant periods of time (Institute for Energy Research, 2012). If subsidies or subsidy-like support[26] is in place for a bona fide reason, then alternative forms of management or alternative fuels should be seriously considered.

E. ALTERING the PLAYING FIELD with FUEL SWITCHING

Transforming an energy system is not a trivial undertaking. After all, energy infrastructure, practices, and industry are slow to change, being traditionally characterized by limited competition, and lengthy periods of research, development, and demonstration (Holdren, 2006a; Flavin, 2008). Nonetheless, rapid change in industries associated with the internet and biotechnology have shown that wholesale transformation can occur in a very short period of time (Ibid; Amaroli and Balzani, 2011; Christensen et al, 2006; Ruttan, 2006; Perez, 2009).

One early study of a global shift to low carbon energy estimated the costs of investment over a fifty year period would equal -1 to +2 percent of gross global product (the worldwide version of gross domestic product) during which the global product would increase by 300 to 500 percent (UNDP et al, 2004 citing Grubb et al, 2002). Other analysis has been accruing on this – each with different assumptions for time scales,

[26] Tax deductions for energy or energy technologies can differ in certain technical definitions from 'pure' subsidies. While deductions and simple subsidies can impact distinct government budget lines, both policy instruments reflect economic support that can have the same net dollar effect for the tax payer (Koplow and Dernbach, 2001; Institute for Energy Research, 2012).

technology combinations, discount rates, policies, etc.[27] Such analyses by country and technological feasibility are also increasing.[28]

The bottom line is there will be a cost associated with change and a cost to maintaining the current path.[29] In either case, much of the existing infrastructure will need to be modernized or replaced. Additional infrastructure will be also required if consumption continues at the current pace. If done strategically, investment choices can bring savings and other gains to an energy system, including improvements in energy security, the environment and public health.

Studies of previous energy system transitions and development provide insights on a range of factors that can matter in a system change (Grubler, 2004; Hughes, 1983; Jones, C., 2009; Martinot et al, 2002; O'Connor, 2010; Smil, 2010, 2004 and 1994;

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[27] See Holdren, 2006a; IEA, 2010a and 2010d; World Economic Forum, 2009; Martinot et al, 2007; McKinsey, 2009; Sawin and Moomaw, 2009; UNEP and New Energy Finance, 2011. For a conversion to strictly renewables, see Jacobsson and Delucchi, 2009.

[28] For country-related studies, see European Commission/EC, 2010; Flak, 2011; Fleten and Ringen, 2009; Johnson et al, 2009; NREL, 2004; PD, 2010; US DOE, 2011a; WEC, 201a; Winkler, 2006; World Bank Group et al, 2010; Yep, 2010 and 2011. For technological feasibility studies, see Arvizu et al, 2011; Jacobson and Delucchi, 2009; Pacala and Socolow, 2004; Sangster, 2010; Schneider, 2009.

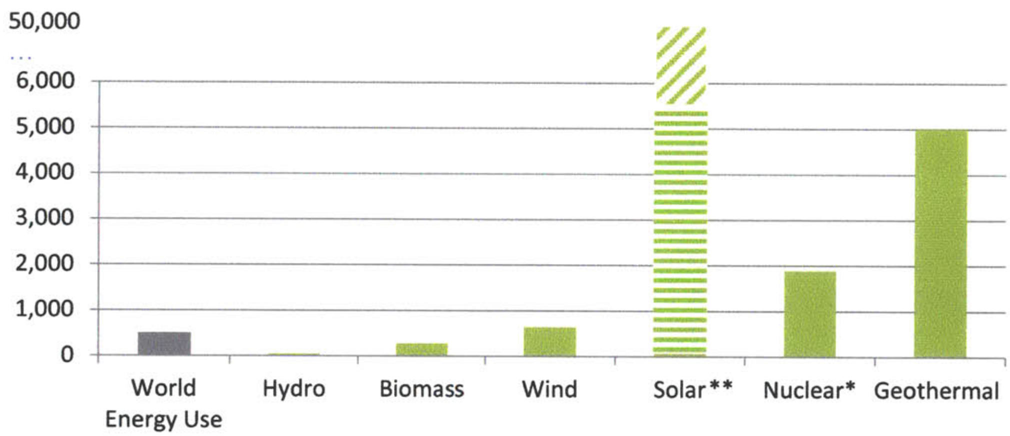
[29] An assessment of an energy path with new (known) policies for 2011 to 2035 estimates a need for investment in energy supply infrastructure totaling $37.9 trillion (2010 $) (IEA, 2011). By rough comparison, the 2010 world economy approximated $75 trillion (purchasing power parity/ppp) (CIA, 2011). The new energy policy path would replace obsolete production facilities and spent reserves, covering increases to meet new demand (IEA, 2011). This assessment breaks down in such a way that roughly half the investment is expected for electricity and much of the rest is anticipated for oil and gas (IEA, 2008c; Jones, R., 2009).

Yergin, 1991 and 2011). The attributes of a particular energy type and adequacy of infrastructure will play a role in modes and timescales for energy delivery. Indigenous technical capacity of a society, types of markets, and governance structure can shape the form and pace with which a country adapts (Grubler et al, forthcoming; Verbong and Geels, 2007; Cleveland, 2008; Perez, 2009; Smil, 2010). Conditions on the ground, like economic booms and busts or the presence of a strong leader, can also shape perceptions of the urgency for change and redefine political agendas. This is a theme that will be explored more in Chapter 3.

Resource Potential for Low Carbon Energy

Understanding resource potential is fundamental for low carbon energy strategies. Figure E1 shows the current world energy use and rough estimates of technical potential for select types of low carbon energy.[30] Based on this information, one can infer that significant low carbon energy change is technically possible. Table E1 expands on this with data including theoretical potentials by fuel type. When considered

Figure E1: Estimates of Energy Resource Technical Potential (EJ/Year) and the 2011 World Energy Use (EJ)



*Source: UNDP et al, 2000; BP, 2011; Bertani, 2003. Note: *Nuclear is EJ rather than EJ/year. **For solar, the minimum technical potential is shown in horizontal stripes and the maximum technical potential is shown with diagonal lines. See Table E1 for data and Johansson et al, 2004.*

[30] Precise definitions for technical and theoretical potential often vary. Technical potential is frequently analogous to 'resource', implying energy that is technically able to be extracted, irrespective of economic feasibility. Theoretical potential refers to energy availability that is deduced as possible based on an understanding of the resource flows, yet which is not feasible to extract, given prevailing technology and economic conditions. See UNDP et al, 2000 for a discussion of assumptions used for fuel potentials in Figure E1 and Table E1 estimates. See also World Energy Council, 2010 for a discussion of reserves and resources, including proved, probable (indicated), possible (inferred) and undiscovered resources.

at an aggregate level, biomass and hydropower rank highest for current use, whereas solar, geothermal, and nuclear energy reflect the highest technical potentials. More

Table E1: Global Resource Base for Select Low Carbon Energy (EJ/Year)

Resource	2008 Use*	Technical Potential	Theoretical Potential
Hydropower	11.6	50	147
Biomass	50.3	276	2,900
Solar energy	0.5	1,575-49,837	3,900,000
Wind energy	0.8	640	6,000
Geothermal energy	0.4	5,000	140,000,000
Ocean energy	0.00		7,400
Nuclear energy	9.85	1,890**	7,100**
Total	73.45		

*Source: Adapted from UNDP et al, 2000, unless otherwise noted. Notes: *2008 use is taken from Moomaw, et al, 2011, and based on direct equivalent accounting. **Technical and theoretical potentials for nuclear energy are in EJ not EJ per year. These nuclear energy potentials reflect open cycle processes. If closed cycle processes were used with fast reactors, technical and theoretical potentials would equal 113,000 EJ and 426,000 EJ, respectively. Solar technical potentials reflect different assumptions on annual clear sky irradiance, annual average sky clearance, and available land area.*

broadly, solar and geothermal energy rank highest for theoretical potentials.

Considering energy availability with scenario modeling, recent analysis by the IEA (roadmaps 2009-2011) and the IPCC (2011) evaluated low carbon energy resource potentials for future energy use through to 2035 and 2080. Both studies found that pathways with substantially reduced carbon intensities (Chapter 3) are attainable with policy being instrumental for overcoming barriers to such change.

F. BARRIERS to CHANGE

A range of challenges or barriers must be taken into account, when considering transitions to low carbon energy.[31] Factors like long turnover timescales, discussed earlier, will matter for adoption of energy technology. Additional challenges can include: incumbency and vested interests (Moe, 2010; Koonin and Gopstein, 2011); path dependence (Arthur, 1989; Unruh, 2000); higher initial costs and lack of capital (PCAST, 1999; IPCC, 2000); information asymmetries (IPCC, 2001); institutional co-evolution (Juma, 2011; IPCC, 2000); appropriability gains in public goods (Anex, 2000; Arrow, 1962; Dosi et al, 2006); and scalability (Fridley, 2010; Koonin and Gopstein, 2011), among others.

Incumbency and Vested Interests

Incumbency and vested interests can impede new energy pathways. Such impediments may be found in technologies, practices, and/or constituencies which have an inherent advantage in the status quo. With this, incumbent actors may exert pressure on government to impose administrative procedures, taxes, trade barriers, or regulations in order to prevent new entrants from challenging the current power structures and undermine existing rents (IPCC, 2000; Olson, 1982).

[31] Barriers, as one might expect, are factors which hinder change. For the purposes of this study, these can include elements, like a limited institutional capacity that may not be recognized at the time of immediate challenge.

Path Dependency and Lock-in

Closely linked to incumbency is path dependence. This notion indicates that prior choices can constrain subsequent options through the quasi-irreversibility of sunk investment; a desire for increased returns; the inter-relatedness of technologies; network effects; or localized learning (Arthur, 1989 and 1994; David, 1985, 1986, 1997; 2000; Puffert, 2010).[32] Path dependence can be found, for example, in forms of suburbanization. If substantial roadways are built and communities become accustomed to high levels of vehicle ownership, dubbed car-centric transportation monoculture (Sperling and Gordon, 2008), opportunities to adopt cleaner and less costly rapid speed rail may be ignored.

Greg Unruh took the concept of path dependence a step further with the idea of carbon lock-in. According to Unruh, industrial economies have become entrenched in fossil fuel-intensive systems through co-evolutionary development of technological and institutional processes driven by returns of scale that, in turn, create persistent market and policy failures (2000 and 2004). This 'vicious cycle' inhibits diffusion of carbon-saving technologies, despite cost-neutral or even cost effective remedies with apparent environmental and economic advantages (Ibid, citing Ksomo,1987). The self-re-enforcing reliance on an incumbent carbon dependent path is not necessarily permanent, according to Unruh, yet it persists in creating systematic market and policy

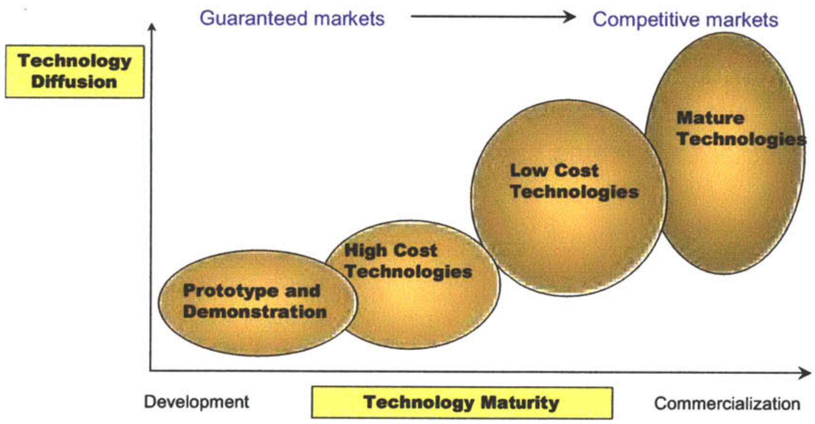
[32] 'Network effects' refers to the value which increases with widespread adoption, such as is evident with telephones and email. 'Localized learning' refers to the way people adapt or 'satisfice' to conform to the choice.

barriers to alternatives such as energy efficiency and renewable energy technologies (Unruh, 2000 and 2004).

Higher Initial Costs and Lack of Capital

Barriers to low carbon energy change also lie in higher initial costs of technology and the lack of capital. A number of low carbon technologies currently cost more than their carbon-intensive counterparts, since the former technologies are in earlier stages of technology development. As technologies mature, prices typically will decrease (Figure F1).

Figure F1: Technology Maturity and Diffusion



Source: Adapted from IEA 2008a, 2008b.

Newly emergent technologies also often entail more significant upfront investment or transaction costs which can be offset over time by sustainability gains. Despite the opportunity for net gains from investment in such technology, there are frequent circumstances in which prospective users do not adopt a desired technology because they lack access to capital (IPCC, 2001; Ki Moon, 2011). A key reason underpinning this hinges on challenging financing terms. Financing of capital is typically based on established returns on investment. Since new technologies do not yet have a track record, their risk is often deemed uncertain.

Information

Information also plays a critical role on adoption of energy. In the absence of adequate information, energy decision-makers may make poor choices (IPCC, 2000; Mitchell et al, 2011). Notably, differences in information can distort not only competition, but affect public perception. Debates over offshore wind in the United States, for instance, might take a different form if prospective, offshore wind communities knew more about studies of post-installation wind farm impacts in Europe (Larsen, 2010; Clausen, 2008).

Institutions

Another type of barrier can be found in institutions that need to evolve in order to effectively address new technologies and conditions (Hargadon and Douglas, 2001; Juma, 2011 and 2005; Ottersen, 2003; Barry, 2006; Mitchell et al, 2011). A current example could include the need to adapt permitting agencies and their related review processes for siting of solar panels and water heaters in urban settings.

Appropriability Gains in Public Goods

Technologies which meet a broader, public goods need,[33] such as energy security or public health, may be hampered in their diffusion for another reason – that of

[33] Public goods are non-excludable and non-rivalrous (Cowan, 2008). Non-excludability indicates that no one can be prevented from using a particular good (Gravelle and

appropriability. This implies that the ability to capture all benefits of broadly-applicable results is less likely (Dosi et al, 2006; Anex, 2000; Arrow, 1962; Mitchell et al, 2011). An automobile manufacturer, for instance, could choose not to produce a technically feasible, low cost and emission-free car if the projected profits appear relatively small compared to broader societal gains.

Scalability

Scalability is another kind of barrier, at times, in which the magnitude of the change presents inherent challenge in and of itself. The earlier discussion of technically available resources showed that the volume of low carbon energy resources is not broadly an issue for widespread conversion to lower carbon pathways. Nonetheless, the sheer size of energy systems involved may serve as a deterrent. That is the point of departure for this study. Four countries of differing sizes have undergone significant low carbon energy transitions at scale. What can be learned from their track records?

G. QUESTIONS to be STUDIED

This study explores the way in which four prime mover countries of advanced, low carbon energy technologies shifted their national energy systems since 1970.[34]

Rees, 2004). Non-rivalrous means that consumption by one person does not diminish the opportunity for consumption of the good by another person (Ibid).

[34] Advanced, low carbon energy technology refers, here, to non-fossil fuel based energy technology for which significant development is evident in the last 50 years. Wind, solar, biofuels, geothermal, and nuclear fall within this group. Hydropower constitutes a more traditional, low carbon energy technology.

Four central questions are examined:

- *Which drivers and barriers appear to be instrumental in the studied transitions?*[35]
- *What innovations and adaptations are significant in the scale-up of low carbon energy and which sectoral actors principally contribute?*
- *What pre-conditions, if any, factor importantly in the energy system transformation?*
- *What patterns or models of change are evident in the energy transitions and how do they compare in terms of indicators for energy system change?*

Alongside these questions is the thesis that major transitions to low carbon energy in this study cannot be deterministically explained by the presence of a relevant energy resource. This will be comparatively revisited in Chapter 8.

H. CONCLUSION

Whatever the reason for switching to low carbon energy -- to extend the life of fossil fuel sources, to create a more sustainable environment, to reduce import dependence, etc, energy system change can emerge from a series of inconspicuous and autonomous events or be a more deliberate endeavor.... The following sheds light on how four countries navigated this terrain.

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[35] Drivers and triggers are both enablers of change, yet encompass slightly different phenomena. Triggers are classed, here, as events; whereas drivers are non-event factors, like the increased interest in energy security.

APPENDIX

Table A1: Select Environmental Stresses due to Human Disruption

			Share of Human Disruption Caused by:			
Physical Stressor	**Natural Baseline**	**Human Disrup -tion Index***	**Commercial Energy Supply**	**Traditional Energy Supply**	**Agriculture**	**Manufac-turing other**
Lead emissions to the atmosphere	12,000 tons/year	18	41% (burning fossil fuel, including additives)	Negligible	Negligible	59%
Oil added to oceans	200,000 tons/year	10	44% (petroleum extraction, processing and transport)	Negligible	Negligible	56%
Sulphur emissions into the atmosphere	31 million tons-S/year	2.7	85% (burning fossil fuel)	0.5% (burning traditional fuel)	1%	13%
Nitrous oxide emissions into the atmosphere	33 million tons/year	0.5	12% (burning fossil fuel)	8% (burning traditional fuel)	80%	Negligible
Particulate emissions into the atmosphere	3,100e million tons/year	0.12	35% (burning fossil fuel)	10% (burning traditional fuel)	40%	15%
CO2 flow into the atmosphere	150 billion tons-C/year	0.05	75% (burning fossil fuel)	3% (net deforestation for fuel wood)	15%	7%

Source: Adapted from UNDP et al, 2004 (originally updated from Holdren, 1992).
*Note: *The human disruption index is the ratio of human-generated flow to the natural baseline flow.*

Table 1 shows shares of select toxic emissions and other pollutants attributable to human disruption. It reflects human-generated intervention versus the natural flow for certain environmental stressors. Lead emissions in the atmosphere, for example, have a natural baseline flow of 12,000 tons per year that is amplified 18 times more by human-based intervention -- 41% of the disruption is attributed to fossil fuel-related activity, 59% to manufacturing- related activity (UNDP, 2004).

Table A2: Costs, Fuel Prices and Capacity Factors for Various Power Sector Fuels

		EC 2008	EPRI 2008
Nuclear			
Overnight cost	$/kw	2552-4378	3980
Fuel price	$/MWh	10.5	8.2
Capacity Factor		85%	90%
Levelized cost	$/MWh	65-110	73
Pulverized Coal			
Overnight cost	$/kw	1295-1865	2450
Fuel price	$/MWh	2.8	1.7
Capacity Factor		85%	80%
Levelized cost	$/MWh	52-65	64
Integrated Gasification Combined Cycle**			
Overnight cost	$/kw	1813-2137	2900
Fuel price	$/MWh	2.8	1.7
Capacity Factor		85%	80%
Levelized cost	$/MWh	58-71	70
Gas**			
Overnight cost	$/kw	622-946	800
Fuel price	$/MWh	7.7	7.6-9.5
Capacity Factor		85%	80%
Levelized cost	$/MWh	65-78	73-87
Biomass			
Overnight cost	$/kw	2617-6580	3235
Fuel price	$/MWh	2.8-5	1.16-2.1

Capacity Factor		85%	80%
Levelized cost	$/MWh	104-253	73-86
Onshore wind			
Overnight cost	$/kw	1295-1775	1995
Capacity Factor		23%	33%
Levelized cost	$/MWh	97-142	91
Offshore wind			
Overnight cost	$/kw	2267-3562	1995
Capacity Factor		39%	33%
Levelized cost	$/MWh	110-181	91
Hydropower			
Overnight cost	$/kw	1166-8549	
Capacity Factor		50-57%	
Levelized cost	$/MWh	45-240	
Solar PV			
Overnight cost	$/kw	5311-8938	
Capacity Factor		11%	
Levelized cost	$/MWh	674-1140	
Solar thermal			
Overnight cost	$/kw	5181-772	4600
Capacity Factor		41%	34%
Levelized cost	$/MWh	220-324	175

*Source: Adapted from IEA, 2010d. **Note: Natural gas-fired power plants may include a number of forms: conventional combined cycle, advanced combined cycle, conventional combustion turbine, and advanced combustion turbine. Reporting for the above version appears to combine conventional combined cycle and advanced combined cycle under IGCC estimates plus conventional and advanced combustion turbines under the gas estimate.*

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Chapter 2: Methods

We can't solve problems by using the same kind of thinking we used when we created them. – Albert Einstein

A. INTRODUCTION

The oil shocks of the 1970s and events, like the 2011 nuclear disaster at the Fukushima Daiichi plant in Japan, bring decision-making about energy switching back into the foreground. Having access to and use of affordable energy without undue harm to the environment, public health, or nation's security is one of the most vexing and unresolved challenges of our time – one that will require shrewd and innovative decision-making.

This research is designed to deepen understanding of recent energy transitions. In particular, it seeks to illuminate underlying influences and decision points which shaped alternative pathways. This is done in deference to national planners and policy-makers who confront the wholesale realities of energy decision-making, often without the benefit of the 'full picture' or scholarly hindsight. The work is interdisciplinary by design and arguably need, since complex problems tied to energy system change do not fit neatly into one disciplinary lens. The social sciences, science and technology, and industry writing all come to bear in this work with special attention on policy, planning and innovation.

The current chapter consists of a discussion of research methods, including criteria for case selection and evaluation. It concludes by noting limits and relevance of the research.

B. RESEARCH DESIGN

This study is based on a qualitative approach which utilizes induction, comparison and grounded evaluation in order to assess four national energy system transitions in the period since 1970. Specific methods include case analysis, process mapping, historical review and semi-structured interviews to develop an integrated assessment of energy transition determinants, innovations and adaptations, and performance.

Selection of Prime Mover Cases

Cases were drawn from a group of approximately 130 countries included in the International Energy Agency energy databases. These are countries from across the industrialization spectrum, encompassing those from the Organization for Economic Cooperation and Development (OECD) plus Non-OECD states. A short list of cases was developed based on those meeting 'prime mover' criteria for the period 1970 to the present. A prime mover in low carbon energy was defined, here, as one in which:

(1) An increase of 100+% was evident in the domestic production of a specific form of low carbon, energy, and

(2) Displacement of at least 15 percentage points was found with a particular low carbon energy form in relation to traditional fuels for a sector of relevance.

This two-pronged filter accounted for absolute and relative growth of a low carbon energy source in a national energy balance representing both diffusion and substitution, respectively. Among the narrowed pool of cases, a diversity of energy types was sought. Final cases included ones which are regularly recognized by industry and academic observers as examples of advanced adoption of newer, low carbon energy technologies.[1] The energy forms that were studied - namely biofuels, wind power, geothermal energy and nuclear power - represent some of the most economically-viable alternatives to fossil fuel that are currently available. For each, technology and science have evolved in the 20th century (Beck, 1999; Demirbas, 2008; Duffy, 2004; Gipe, 1995; Goldemberg and Lucon, 2010; McGowan and Connors, 2000; MIT, 2006; Wyman, 1999; Yusuf et al, 2011).

Grounded Theory Approach utilizing Variance and Process-based Methods

Focusing on the national energy system as the unit of analysis, this study adopted a grounded theory approach to inductively conduct research (Glaser and Strauss, 1967; Martin and Turner, 1986).[2] Various forms of data collection, including semi-structured

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[1] Note: Low carbon energy, such as hydropower, reflects a more traditional energy source used at scale.

See also Aquamarine Power, 2010; Baker, 2010; Climate Institute, undated; Combs, 2010; Delmas and Heiman, 2001; Garcesz, undated; Han, 2008; International Geothermal Association, 2011; Lacey, 2009; Logadottir and Lee, forthcoming; Ling, 2010; Massachusetts Institute of Technology/MIT, 2006; Mims, 2008; Nordic Council of Ministers, 2011; Ragheb, 2010; Sawin, 2001; Sovacool et al, 2008; Walsh, 2009; World Energy Council/WEC, 2007 and 2010; World Nuclear Association/WNA, 2011.

[2] When a country or national system is a unit of analysis, 'outputs' can be construed in simplified form as an outcome of deliberate and centrally coordinated decision-making, organizational dynamics, or bureaucratic politics, among possibilities. This is not unlike

interviews; historical record review; and extraction of energy, economic, environmental and societal trends from different databases, allowed early-staged identification of developments and influences in energy trajectories, based on the strength of the data. Chronologies of developments were overlaid within each case to create integrated process maps of national energy trajectories. These maps served as the basis for exploring the sequencing and causality of changes. Findings from preliminary mapping were then more rigorously explored in subsequent rounds of interviews as well as with additional historical record review, and case analysis.

This research design drew upon variance and process-based methods which differ fundamentally in how change is conceptualized (Poole, 2004). The variance method explains change in terms of the relationship between independent and dependent variables, whereas the process method explains an outcome on the basis of a sequence which leads to such an outcome (Ibid; also citing Mohr, 1982 and Poole et al, 2000). To illustrate the distinction, a study of industrialization with the variance method might focus on the strength of causality between regional economic drivers and industrial advance, whereas the process approach may consider whether the sequence of economic drivers would produce the same level of industrialization, absent technology change at various points (Ibid).

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the governmental behavior examined by Allison and Zelikow (Allison, 1969; Allison and Zelikow, 1999). By design, the grounded theory-based, systems perspective employed in this research allows for such multiplicity of ways in which outcomes are effectuated and interpreted.

In this study, the variance method was used to test relationships, assessing the causes of change (independent variables) evident in an energy system transition (dependent variable). This method also provided some understanding of energy systems in the context of other casual processes at work (i.e. adaptations and innovations) in order to gain fuller insight into the relevance of sectoral contributions to the larger energy system change (Poole, 2004, citing Goodrich and Salancik, 1996).

Somewhat differently, the process method was used to ask how and why a change occurred (Langley, 2007). This latter method focused on the way an outcome was defined, constituted, and adapted in evolving processes (Ibid, citing Tsouka and Chia, 2002). By evaluating processes, the relevance of critical events and turning points, context, formative patterns, and causal factors that influence event sequencing were more fully assessed (Ibid).[3]

Proposition

To classify energy transitions, this study initially proposed a simple and provisional framework representing types of system change along a continuum of emergent versus

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[3] Critical events and turning points, like an oil shock of the 1970s, can be viewed as triggers associated with outcomes or impacting energy decision-making.

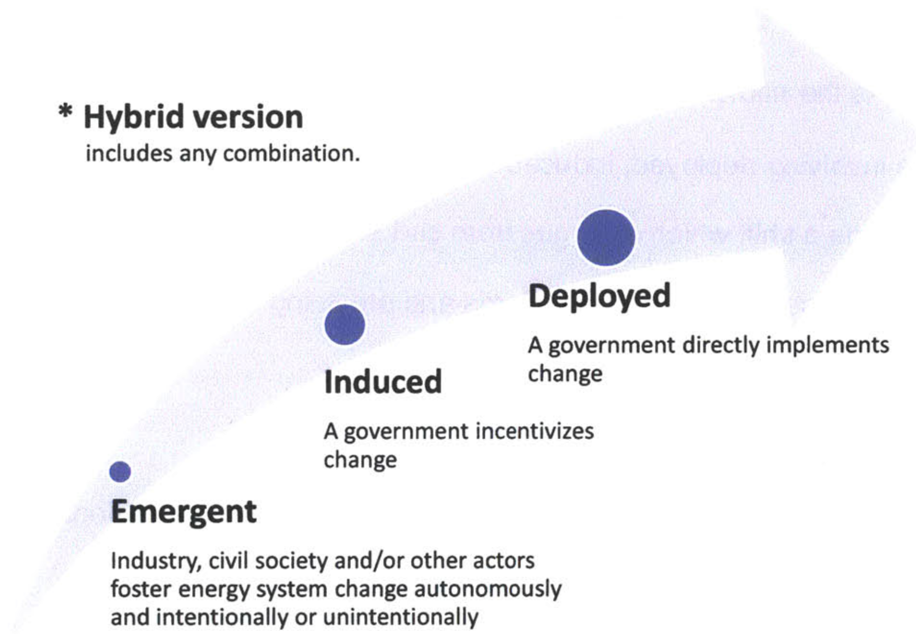
Contextual relevance refers to environmental aspects that can enable or hinder transformative change. For example, a highly risk-averse environment is not as naturally conducive to a system change as a more adaptive/entrepreneurial one may be.

Finally, causal factors which influence event sequencing may be found in drivers, like the emergence of sustainability concerns, which redefine priorities.

These elements naturally can overlap.

induced versus deployed change with a hybridized blend being a fourth category. Figure B1 illustrates the framework, depicting less government intervention on the left-hand side and greater intervention on the right.

Figure B1: Continuum of Energy System Change



1. **Deployed change** – In deployed change, a government directly implements a shift to a new form of energy through, for instance, construction of relevant infrastructure and the physical provision of energy.

2. **Induced change** – With induced change, an energy system shift is spurred by policies, like subsidies to enhance the favorable pricing of a new fuel.

3. **Emergent change** – Emergent change to a new type of energy occurs for reasons other than active deployment or inducement by a government. Actors in industry or energy users, for example, may alter practices to meet individual interests which create a shift. Such emergent may be seen with end-users choosing to diversify their energy sources in response to service disruptions, safety concerns or fuel price volatility.

4. **Hybridized change** – As the name suggests, a hybridized shift occurs through a combination of elements involving deployed, induced and/or emergent change. An example, here, would include a shift which emerges from civil society or industry that is then amplified by government setting industry standards and providing investment credits.

The proposed framework can be applied to local, regional, national and supra-national levels of energy system change. In this research, energy system change is viewed at the national level, therefore local governmental actors would be classed among other actors. It is also useful to emphasize that an energy system change may be linked to an explicit goal, an implicit goal, shifting goals or no goals. A shift toward low carbon energy that is not shaped by an objective to reduce carbon could occur for coincident reasons, such as a desire to increase energy independence or to reduce the effects of oil price flux on a country's trade balance.

Comparative Case Analysis

Comparative case analysis was done to determine how and why transitions to low carbon energy were effectuated in certain countries since 1970. As opposed to surveys, experiments or statistical analysis, case studies allow for a more in-depth exploration of socio-political dynamics and can reveal linkages that other methods may not (Yin, 1994). Utilizing a multiple, rather than a single, case approach suited this study's purposes, since it highlighted commonalities and supported the development of a conceptual framework. The number of cases utilized was not exhaustive nor fully representative in the strictest sense, but reflected an illustrative group of newer, low carbon energy technology examples for in-depth evaluation. The multi-case approach is preferable as findings generally hold greater weight if they can be justified with reference to more than one case.

To draw out basic case similarities, each case entailed a national energy system comprised of actors, inputs, and outputs with systemic architecture connecting them in a complex network of energy-centered flows over time - including extraction, production, sale, delivery, export, regulation, consumption, etc. Each country has a constitutionally-mandated set of institutions for effectuating policy. Moreover, decisions and actions related to energy manifest in energy production, consumption and import/export patterns embodied within a national energy trajectory.

The cases also differed importantly from each other. First, each case focused on a discrete form of low carbon energy. The countries also have varied sizes in terms of land mass, population and economy. The approaches to governance in each country, as well as development paths and cultures also varied over time. Recognizing these distinctions, the study drew upon the 'most different systems approach' which tests to see whether a relationship between variables is replicated across a wide variety of different settings. If such a relationship exists, there are grounds for arguing that a causal link exists between the variables of different settings (Huitema and Meijerink, 2009, citing Hopkins, 2002).

Interviews

More than thirty interviews per case were conducted, totaling 120+ overall. Typically, interviewees were purposively selected to represent a range of sectoral interests and expertise, drawn regularly from those who critically wrote about advanced aspects of the relevant subject, or were involved in organizations/roles affecting or affected by relevant developments. These individuals included members of government, academia, industry, scientific laboratories and civil society. A diversity of views and historical points of engagement was sought. Semi-structured interviews were completed in person, by telephone and by email.

In an effort to gain more holistic understanding of energy transition phenomena, questions were posed generally in two formats:

Group A:

Open-ended questions centered on drivers, barriers, innovations, sectoral contributions and key actors.

Group B:

More targeted questions focused on adaptations in key areas like science and infrastructure, as well as other particularities which emerged and appeared to be relevant to a case (See discussion in Section C).

The open-ended nature of Group A questions provided an opportunity to more fully learn about forces in play and interviewees' rationale for weighting relevance, among other points of interest. The more targeted nature of Group B categories was designed to discern specific elements and their linkages to energy development.[4]

Data

Data on energy use was drawn principally from the International Energy Agency, the International Atomic Energy Agency (IAEA) and United Nations databases as well as Carbon Dioxide Information Analysis reporting, World Development Indicators, and International Monetary Fund data.[5] Historical documentation of energy policy, socio-

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[4] See Auti, 2002; BP, 2011; Chatterji, 1988; Cleveland, 2009; Crease, 2004; Dorian et al, 2006; Goldemberg, 2004; Grubler, 2004; Hultman et al, forthcoming; IPCC, 2007; James, 1989; Jones, 2009; Jorgenson, 1984; Munisinghe, 2004; Sachs, 1999; Smil, 2003, 2010; United States Department of Commerce, 2011; and UNDP et al, 2000. See also Chapter 3.

[5] International Energy Agency, http://www.iea.org/stats/index.asp; the International Atomic Energy Agency (IAEA), http://www.iaea.org/; United Nations, http://www.unstats.un.org; Carbon Dioxide Information Analysis, http://cdiac.ornl.gov/ World Development Indicators, http://data.worldbank.org/data-catalog/world-

economic developments and industry patterns was also used to evaluate societal elements tied to the national energy pathways. Such documentation was usually derived from sources like governmental agencies, academia, industry associations, and intergovernmental organizations detailing laws, regulations, and market developments. The reliability of information sources, as with any research input, carries questions, so the information was cross-referenced across types of sources and sectors, where feasible.

C. ANALYSIS

The research examined national energy trajectories in energy balances, production, consumption, and energy imports/exports. Such trajectories were considered in the context of (1) science and technology, (2) industry and infrastructure, (3) the economy and environment, (4) governance and society, as well as (5) other conditions which were determined to be relevant in case analysis. The first four dimensions were explored in initial data collection and are understood to be influences which affect and/or may be affected by energy development (Chapter 3). The fifth dimension allowed space for factors which fell outside the recognized categories or which cut across them.

D. CRITERIA for EVALUATION

To evaluate causality and durability of a sustained transition, two basic kinds of parameters were used: influences and yields. For the purposes of this study, influence

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development-indicators; International Monetary Fund, http://www.imf.org/external/data.htm.

was generally more qualitative, gauging the relative impact of drivers, barriers, adaptations and contributions on a transition. Yield was used to gauge outcomes and in many cases could be quantified or physically observed.

Influences

For the influence of determinants, the study considered the extent to which a specific factor was indicated across multiple source explanations, as well as the preponderance of its logical fit with the data and conditions. Where possible, qualitative weighting was empirically corroborated with corresponding changes in yields. If, for example, a robust policy change (1) was emphasized in historical records and interviews as having a positive effect on the adoption of low carbon energy, (2) logically resonated with observable conditions, and (3) appeared to be substantiated by data showing capacity increases, absent other strong explanatory dimensions, then the policy was deemed to be a key driver. Unanimous validation or agreement across all sources was not expected. When notable differences in source insights were found, they were indicated.

Yield as a Measure of a Sustained Transition

Measures of durability in a sustained transition can focus directly on the energy balance as well as on ancillary developments in costs, society, and industry. Among the range of possible yield indicators, this study evaluated the following:

- Changes in the relative and absolute amounts of a studied form of energy in an energy mix
- Cost improvements and competitiveness

- Societal acceptance, and
- Industrial development.

The change in the energy mix was gauged in absolute and relative terms to capture diffusion and substitution. For example, an energy mix could change from using 10% to 20% of a studied form of energy in relative shares. It could also indicate absolute growth of the same energy by 45%. Specific to costs, two patterns were examined:
(1) whether cost improvement was evident over time, as for instance with a reduction in installed costs; and (2) if costs were competitive in the 1970s and whether they are now. For societal acceptance, were there significant signs of resistance in the early and latter stages of the transition and do they appear to be significant? Societal positions were assessed principally through the news, interviews, and/or historical record, for example, of protests or governmental changes. For industrial development, generally-recognized signs were examined to see if a related industry took root and flourished, for example, with growth in relevant exports and/or market leader positioning.

E. LIMITS of the STUDY

This study had a number of expected limits. Specific to research design, the cases in this study were not randomly selected, represented a small set of cases and had a discrete dependent variable. Criticisms of this approach will contend that selection bias or problems related to a small N can produce flawed inferences (Geddes, 1990; Achen, 1986; King, 1989). These limits are openly acknowledged for their challenges in design rigor. However, phenomena often exist in imperfect experimental design conditions, where studies can nonetheless advance knowledge by illuminating critical insights, plausible causal linkages, and anomalies that are unexplained by existing theory (Geddes, 1990; Kuhn, 1996). For the current study, commonalities and differences across a range of indicators in energy transitions were considered to allow for the development of practical explanatory insight and theory into this phenomenon.

The choice of time-spans to study carried another kind of challenge. One could argue that the end-point of an evaluated times series shapes the observed phenomenon (Geddes, 1990). By extension, the starting point of a study holds similar relevance. Recognizing these temporal dynamics, a common time horizon was used, beginning with 1970 to capture a baseline predating the first oil shock of 1973-1974. The endpoint is the present, essentially the period of this writing. Utilizing a common time period allowed for comparative evaluation of influences from global events, yet technology trajectories within various countries, even if 'responding' to similar global conditions, can have differing points of initiation and times spans for growth. Such differences may mean that fuller explanatory accounting will not be possible until future research retrospectively reviews completed technology life cycles. In any event, four decades of coverage allows ample time for many effects shaping energy adoption to be internalized.

The precise recall of key actors represented another research challenge. The retrospective and historical nature of this study allowed ample opportunity to capture a range of influences affecting infrastructure, institutions and practices, yet this also could be counteracted in part by changes in memory. Oral historians and psychologists refer to the accuracy problem as an issue with the reliability and/or validity of recall (Hoffman and Hoffman, undated). [6] To account for this, open-ended questions were employed with actors from varying eras as part of the interviews. Alternative explanations were raised and questioned. Additionally, interview findings as well as written accounts were cross-referenced against methodological inputs, where possible. This triangulation can serve to mitigate many issues of recall, but may not fully account for a related challenge of societal over-writing, where one person's flawed narrative is repeated in historical records, becoming part of the wider, societal accounting. For this, memory-based information was tested against quantitative data trends, where possible. While recognized as an imperfect device, it nonetheless served a purpose to reconcile insights.

When studying multiple countries or technologies, cultural and technology-specific differences can introduce idiosyncratic challenges to cross-case comparison which are not generalizable. Technology A, for example, may be easier to deploy than Technology B. Similarly, Country C may be less risk averse than Country D. For the purpose of knowledge accumulation on energy system change, key distinctions were sought and

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[6]. This dilemma goes hand in hand with historical reporting and analysis. In Thucydides' introduction to the history of the Peloponnesian War, written in 431 BC, he highlights this in saying, "[m]y conclusions have cost me some labour from the want of coincidence between accounts of the same occurrences by different eyewitnesses, arising sometimes from imperfect memory, sometimes from undue partiality for one side or the other (Hoffman and Hoffman, undated, citing T. Leahey, 1987 and Thucydides, 431 BC).

raised in this study with an understanding that some aspects would require further investigation.

The way that similarities and differences were interpreted is a design consideration for all forms of research. Assumptions and approaches used by a researcher can influence the way a studied phenomenon appears or is explained. Similarly, later readers' cognitive points of reference may produce alternative interpretations (American Institutes of Research, 2006, citing Ginsburg and Gorostiaga, 2003, Kohn, 1987 and Sztompka, 1988), resonating with what Herbert Simon calls 'bounded rationality' (Simon, 1957, 1990, and 1991). While it is not possible to anticipate the full range of framings by current and future actors, this consideration was acknowledged with key points of reference explained.

In practical terms, a number of other research limitations are worth noting. The study does not purport to be fully systematic or comprehensive. It is by necessity, a 'first cut'. Variation existed in information/data uniformity, quality, completeness, and access. Translation was also used in areas where this researcher was not fluent. Finally, sample pools of not only the cases, but the technologies, interviewees and time-spans, without question, can be expanded.

F. RESEARCH MERIT and RELEVANCE

Despite the acknowledged limitations, intensifying challenges of energy use underscore a need for alternative strategies at a meta-level. As an in-depth comparison of four discrete, low carbon energy transitions for the period since 1970, this study may provide practical insights for policy-makers on tools, better practices, and relevant circumstances during which to mobilize. In more academic terms, this study can serve to strengthen theoretical inquiry into energy transitions, technology change and policy/planning with the conceptual frameworks which are proposed.

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Chapter 3

Beyond Malthus

Evolution is a sequence of replacements. - Elliott Montroll, Physicist, 1978

A. INTRODUCTION

A century ago, a national decision-maker examining the energy landscape would have seen an emergent and uneven use of fossil fuels, early-staged electricity diffusion, negligible automobile ownership, and unfinished questions on the merits of electric vs. ethanol vs. petroleum-fueled vehicles (Smil, 2010). Such a decision-maker probably would not have foreseen nuclear generation, gas turbines, aviation or space travel (Ibid).

A similar decision-maker in current times would see limits to historically subsidized fossil fuels, regular challenges to the stability of energy supplies, and compounding environmental effects of energy use. As was evident with earlier periods, breakthroughs in research or societal developments are expected, but not assured. Key developments can be game-changers, but when and how they occur remains an open question.

Today's public discourse on energy often emphasizes the importance of integrated strategies that include fuel switching to low carbon energy, enhanced efficiency and conservation. In line with these, energy writing often envisages change with roadmaps or invokes the need to accelerate innovation.[1]

This study adds to current understanding with empirical analysis and insight from contemporary examples of energy transformation. The current chapter answers a number of fundamental questions:

- What are common dimensions of national energy transitions?
- What does scholarship tell us about meta-level change and innovation?
- What is known about rates of change and prospects for accelerating technology innovation in the context of national energy development?

B. ENERGY TRANSITIONS

Energy transitions are generally understood to be long-term processes of change in energy sources, delivery or use. These transformations can be quantitative or qualitative in form with an example of the latter being a move toward greater energy density through fuel switching from wood to coal. Both kinds of shifts can include changes in end-user technology, as was seen in the rise of consumer electronics.

[1] See Goldemberg and Lucon, 2010; Grubler et al, forthcoming; Anadon et al, 2011; International Energy Agency/IEA, 2009a, 2009b, 2010a, 2010b, 2011a, 2011b; IEA and Nuclear Energy Agency/NEA, 2010; Intergovernmental Panel on Climate Change/IPCC, 2007; Jefferson, 2008; Lester and Hart, 2012; Moomaw et al, 2011; Mitchell et al, 2011.

Common Factors in Energy Transitions

Historical writing on energy trajectories often highlights the influence of resource availability, knowledge, technology, practices, infrastructure, economics, institutions, and policy (Smil, 2010; Cleveland, 2008; Fouquet, 2010; Grubler, forthcoming; Jones, 2009; Yergin, 1991 and 2011).

Resource availability generally refers to the supply endowment of a form of energy and the correlated ability to access it. Wind energy resources, for example, are available worldwide (Wiser et al, 2011), yet only in recent years have they been tapped to meet at least 10% of regional electricity demand. What is known about energy resources and what we use to harness them raises the next set of factors.

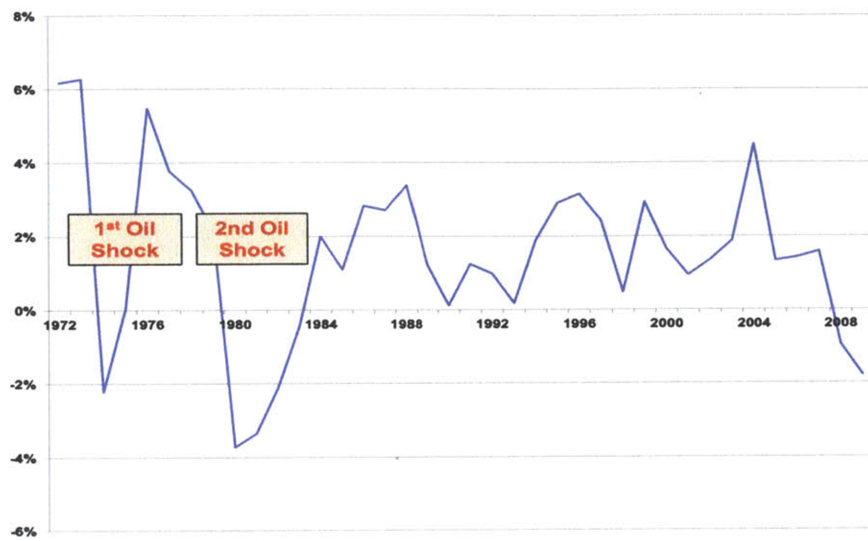
Knowledge and technology matter importantly in energy development since discoveries and technology commercialization can alter the array of options that are available. One need only look to advances in automobile and fuel technology to see this point. Breakthroughs in the internal combustion engine and petrochemical refining enabled gasoline-powered vehicles to progress rapidly in the 20^{th} century. Nevertheless, more recent developments in battery storage technology combined with some revised thinking about fossil fuel dependence have led automobile manufacturers to commercialize electric vehicles (EV), like the Nissan Leaf and Mitsubishi i-MiEV, as well as hybrid electric vehicles (HEV), including the Toyota Prius and Honda Civic (Ibid; PBS, undated; Hybrid cars, undated).

Societal practices also factor in the way energy supplies are developed, produced, and used. Changes, for example, in how we illuminate -- from whale oil to kerosene to electricity -- occurred in tandem with related shifts in supply sourcing from hunting to exploration and finally to managing centralized power plants (Applebome, 2008; Kovarik, 1998; Fouquet, 2011). If traced, these kinds of adaptations will also reveal multiplier effects in how people's diurnal patterns are redefined. Once lighting was readily available 24 hours a day, certain activities, like manufacturing, continued around the clock.

Like the above factors, infrastructure has crucial relevance in energy trajectories as the physical architecture within which energy production, delivery and use are carried out. As a point of illustration, developments in liquefaction plants and liquefied natural gas tankers radically altered parts of international energy markets by allowing natural gas to be shipped securely from distant or remote locations, unconstrained by regional pipelines (Smil, 2010; Center for Energy Economics, undated).

The influence of economics also carries obvious significance for energy transitions in pricing, capital mobilization and investment decisions, among possibilities (UNDP et al, 2000). The global oil price shocks of the 1970s and early 1980s provide a compelling example of how changes in economics can dramatically affect energy use. During the price shocks, namely 1973-75 and 1979-83, radical declines in worldwide consumption of petroleum were readily apparent (Figure B1).

Figure B1: Year over Year Changes in Global Oil Consumption, 1971-2009



Source: IEA data, 2011.

In addition, institutions and policy play a role in energy transitions by providing socio-political mechanisms through which energy choices are vetted and implemented. The founding of the International Energy Agency (IEA) in response to the oil crisis of 1973-1974 represents a significant institutional development in the energy landscape. Established as a means for OECD energy-importing nations to collectively co-ordinate strategic oil reserve policies, the IEA has evolved to not only mitigate major oil market disruptions, but to regularly inform energy decision-makers worldwide with reporting and scenario analysis (IEA, 2012).

Historical Examples of Energy Transitions

Much of the critical work on energy trajectories to date centers on quantitative modeling or targeted analysis of certain dimensions of change (Marchetti and Nakicenovic, 1979; Grubler 2008b; Grubler et al, 1999a; Nakicenovic et al, 1998/1999; Smil, 1994, 2004, and 2010; Jones, 2009). Such research contributes importantly, yet improved understanding will also depend in part on analytical probing of the vetting and realignment dynamics of such transitions. The following three examples illustrate underlying elements at work in historical energy shifts.

The shift in the British navy's energy use from coal to petroleum, for example, highlights the significance of a decision-maker responding to changing conditions. In 1911, then British Home Secretary Winston Churchill opposed fuel switching for the British navy, seeing merit instead in a continued use of domestically-sourced coal. Yet as international tensions heightened with Germany in the period predating WWI, now First Admiral of the Navy Churchill changed his thinking, prioritizing naval tactical performance on the basis of power, efficiency, speed, and flexibility. This shift in strategic focus from domestic fuel sourcing to fleet performance manifested with Churchill pushing the naval fleet to rely heavily on oil imported from Persia (Churchill 1928 and 1968; Churchill and Heath, 1965; Yergin 2011 and 1991).

The more recent adoption of nuclear power illustrates the importance of strategic thinking and spillovers. After the bombing of Nagasaki and Hiroshima in WWII, American Admiral Hyman Rickover was dispatched with a group of naval officers to identify new applications for nuclear energy (Rockwell, 2002; Yergin, 2011; Naval History and Heritage, undated). Recognizing the significance of nuclear power for submarines in improved fuel sustainability, storage weights, and travel ranges, Rickover set about adapting naval expertise and ship design to incorporate the new energy technology into the American submarine fleet. After just three decades, more than 400 nuclear-powered submarines were operational or in the process being built worldwide (World Nuclear Association/WNA, 2011a). Nuclear reactor designs that were used for submarine propulsion, namely pressurized water reactors, were adapted for the power sector. This approach to power generation now produces the majority of the nuclear powered electricity in the 435 commercial reactors in operation today (Ibid; WNA, 2011b, IAEA-PRIS, 2012; Chapter 6).

The energy shift from wood to coal in England reveals how not only prices, but societal perception and learned practices carry significance in energy choices. This earlier conversion began in the 1500s and 1600s, when the growth of cities and deforestation practices produced conditions in which firewood needed to be shipped greater distances (Rhodes, 2007; Fouquet, 2010; Brimblecombe, 1987; Landes, 1969). As the price of firewood increased, less wealthy citizens shifted to coal. However the nobility, including Queen Elizabeth I, maintained the practice of using wood, as coal was considered to be a less clean option (Ibid). When King James VI of Scotland assumed the throne of England and Ireland, he drew upon knowledge utilizing less sulfurous coal from Scottish practices to convert royal energy use from firewood (Brimblecombe, 1987; Rhodes, 2007). This 'royal action' influenced the nobility's view of coal, bringing practices in line with the rest of British citizens. Further developments in steam engines and canal systems extended the adoption of coal with efficiency improvements in coal mining, as well as steam-powered rail transport that enabled new markets to be created (Ibid; Fouquet 2010).

C. USEFUL THEORIES on META-LEVEL CHANGE

When developing more comprehensive analysis of energy transformations, theory on meta-level change from economics, the history of science, policy and socio-technical fields of study can provide a basis for useful framing. Ideas on techno-economic paradigms (TEP) leverage long wave theories of business cycles to describe transitions in terms of inter-related technical and organizational innovations which shape technological revolutions (Kondratiev, 1926 and 1935; Schumpeter, 1939; Rosenberg and Fristchtak, 1983). This line of theory indicates that a new logic, including research rationale and norms, replaces previous thinking over the course of five or six decades, guiding the upgrading and modernization of existing industries to harmonize or synergize with the new dynamic industries (Freeman et al, 1982; Dosi et al, 1988; Perez, 1985, 2002, and 2004a; Schumpeter, 1939; Freeman and Louca, 2001; Marchetti, 1988).

The above notion of a new logic aligns with writing on paradigm shifts where contemporary conditions change and cannot be fully reconciled with prevailing thinking. History of science theorist Thomas Kuhn put forward the notion of paradigm shifts by pointing to knowledge dissonance which leads to a new paradigm that is incommensurate with and eventually replaces a legacy version (1962). Somewhat differently, Deiter Helm argues that a new paradigm builds on the strengths of a legacy (2007). Going further, Helm suggested that key changes in previous energy markets, for example, occurred when the costs and inadequacy of the status quo become so significant as to undermine conventional wisdom. In such conditions, shortcomings must be politically apparent to mobilize change, as with a clear threat to the energy supply (Ibid).

Socio-technical system writing on multi-level perspectives (MLP) provides a slightly different basis for thinking about complex adaptations. This framework draws on sociology and evolutionary economics to describe long term and large-scale system changes in which 'radical technologies co-evolve with changes in markets, regulations, infrastructure, user practices, industrial networks, cultural meaning and scientific understanding' (Geels, 2005). In this framing, system innovations generally result from linkages between processes at niche, regime and landscape levels (Geels, 2004; Geels and Schot, 2007).[2]

Interestingly, the TEP and MLP theoretical lines began to converge when Freeman and Louca (2001) introduced their layered model of a sub-system which includes science, technology, politics, economics, and culture as key elements. They argue that change occurs when 'mal-adjustments across the sub-systems create crises and opportunities for breakthroughs' (Ibid; Kattel et al, 2009).

[2] Niches are incubation spaces for radical novelties that are shielded from mainstream market selection (Geels, 2006, citing Schot, 1998). Regimes encompass cognitive routines, patterned development, regulatory structure, lifestyles related to technology systems, and sunk investment in equipment, infrastructure and competency (Geels and Schot, 2007; see also Nelson and Winters, 1982; Unruh, 2000). Landscapes refer to the broader, exogenous environment and include macro-economic conditions, culture and macro-political developments (Geels and Schot, 2007).

While all of the above literature provides a useful way to consider co-evolution and realignment in relation to change, that on techno-economic paradigms and multi-level perspectives positions energy transitions within larger, meta-level developments in a way that can mask critical elements of the energy system (Grubler, forthcoming). Recognizing this tradeoff, the current study focuses principally on the influence of forces in national energy systems, while also acknowledging dynamics of the broader enabling environment.

D. SUSTAINABILITY at the CROSSROADS

The planet recently surpassed a milestone with the birth of its 7 billionth inhabitant (UN News Centre, 2011). At that juncture, questions persisted about the sustainability of society's current patterns of energy use (Chapter 1; Ki-moon, 2011; Sustainable Energy for All, 2011; Goldemberg and Lucon, 2010). What this implies is worth some discussion.

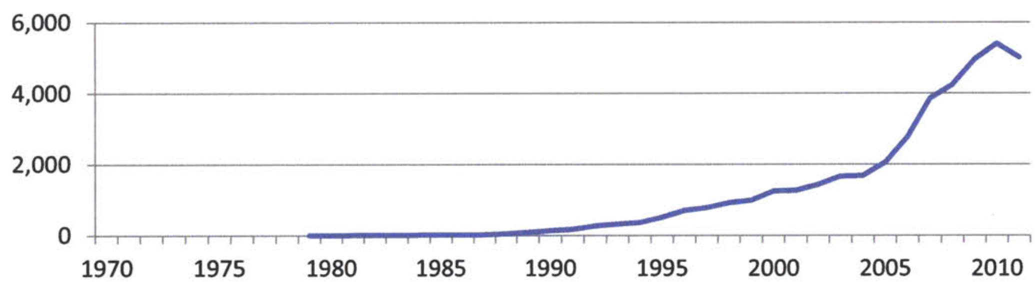
Sustainability

British writer Thomas Malthus is widely credited with early ideas about the way natural resource limitations constrain societal growth (1826). The 1972 Founex Report, the 1987 Brundtland Report, and the 2005 United Nations General Assembly brought Malthusian thinking forward by prioritizing sustainable development - three interdependent and mutually reinforcing pillars encompassing the environment, economics and society -- across generations. This co-mingling of what can be competing priorities has been subject to criticism for its loose definition and imperfect form of measurement (Bartlett, 1997/1998; Daly, 1996; Hecht, undated; Taylor, 1992). Here is where the concept of sustainability may provide some useful traction, if employed in terms of durability or viability (Sathaye et al, 2011). The current study employs this latter definition of sustainability as gauged by factors outlined in Chapter 2.

Sustainable vs. Renewable vs. Clean vs. Low Carbon Energy

As the topic of sustainability has grown in coverage (Figure D1), usage of sustainable, renewable, clean and low carbon energy have somewhat become blurred (Sathaye et al, 2011; Helm, 2007).[3]

Figure D1: Newly Published Articles on Sustainability in Journal Index SCOPUS, 1970-2011



Source: SCOPUS, accessed December, 31, 2011, covering life sciences, health sciences, physical sciences, and social sciences and humanities.

Sustainable energy can be defined *generally* as a durable energy supply or more rigourously as the above energy supply that is extended inter-generationally in a way which does not unduly undermine society, the economy or the environment. Renewable

[3] Even with one term, like renewable, definitional subtleties matter for instance when grouping bands of technologies for renewable portfolio standards.

energy typically refers to energy forms which naturally regenerate. A more rigorous version of this term would stipulate that regeneration must occur in a way which exceeds or matches the draw-down of the energy source. Clean energy typically refers to power use that does not pollute (Mormann, 2011). Low carbon energy can be described as a form of energy which emits less carbon, but one can then ask whether this refers to the life cycle of the fuel or one stage of its management, such as production or consumption? Another logical question is what baseline does one use to gauge low carbon energy gains? A few examples are provided to illustrate these distinctions.

- Natural gas is sometimes classed with low carbon fuels to distinguish it from more carbon-intensive coal and petroleum fuels (Bauen, 2006). If gas is grouped in such a manner, it would represent a low carbon fuel that is not renewable.

- Another nuanced classification can be seen with nuclear energy. If one discounts its waste (Chapter 6) and focuses on the limited emissions of nuclear energy, it can be categorized as a source of clean energy that is not renewable.

- Renewable energy can also be managed in ways which are not sustainable or low carbon. Extraction of geothermal energy, for example, can radically draw down the heat or steam from its source (Chapter 7). In such a case, the energy source is renewable, but not sustainable. Somewhat differently, the production and use of biomass can result in pollution, including CO_2 (Searchinger et al, 2008; Fargione et al, 2008; Porter et al, 2008). Depending on the definitional bounds, this fuel type could be renewable, but not low carbon energy.

What obscures the distinctions between sustainable, renewable, clean, and low carbon energy often appears to be the way a specific type of energy is managed from end to end (not just in its sourcing). If mainstream terms like 'green' energy are then also acknowledged with policies and conventions that are globally being developed (REN21, 2011; International Sustainable Energy Assessment, undated), the need for clarity becomes more evident. In short, current reporting, literature and energy-environmental agreements may not explicitly stipulate what is included or excluded in writing pertaining to sustainable, renewable, clean, and/or low carbon energy. Such definitional laxity may exist in part because continuous changes are underway in technology and management practices. For the purposes, here, low carbon energy refers in the classical sense to non-fossil fuels, namely renewable and nuclear energy. Sustainability, durability and viability of energy transitions are used interchangeably.

E. KNOWLEDGE, TECHNOLOGY and INNOVATION THEORY

Knowledge, technology and innovation are known to be powerful forces of transformation (Schumpeter, 1939; Landes, 1969; World Intellectual Property Organization/WIPO, 2011).

Knowledge

What constitutes knowledge and how is it derived is subject to continued debate. Aristotle, Kant, Wittgenstein, Gettier, among others, have weighed in on this over the centuries. Among positivists, knowledge accrues when science confirms theories through the application of strict scientific methods that may be reproduced and reviewed by peers in the academic or professional community (Little, 1995; Casti, 1989). By contrast, knowledge in the post-positivist school of thought is a construct in which the perceiver of knowledge is intricately involved in its development.

Knowledge can also be understood in terms of its sourcing and level of established authority. Expert knowledge, often referred to as scientific knowledge, is typically thought of as insight that is tested through disciplinary investigation and accepted by scientific peers. By contrast, local knowledge is "knowledge which does not owe its origin, testing, degree of verification, truth, status, or currency to distinctive professional techniques, but rather to common sense, causal empiricism, or thoughtful speculation and analysis" (Lindblom and Cohen, 1979). Notably, expert knowledge is conventionally recognized as an established basis for problem resolution, but it has been proven to be flawed or simply does not yet hold an answer. Here is one area where local knowledge can add important value to test assertions, fill information gaps, and enhance the legitimacy of decisions. The way knowledge evolves in relation to energy system change will be a subtheme in the cases which follow.

Technological change

Technological change can be fundamental to energy transitions.[4] The nature of technology change is often categorized as incremental or radical in form (Abernathy and Utterback, 1978; Dosi, 1982; Grubler, 1998; Grubler et al 1999a and 1999b).[5]

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[4] Technology refers to hardware and software, like equipment and computer applications, yet it can also imply products, processes, devices and practices (Grubler et al, 1999a and 1999b). The definition may extend further to include inputs like energy, raw materials, and labor; production knowledge and ideas as well as social institutions (Ibid; Dosi, 1982). For the purposes of this study, technology is defined to include hardware, software and material inputs (i.e. energy and raw materials), using the term 'system' to capture the broader conceptualizations of technology. Related dimensions, like knowledge and practices, are considered under their own labels.

[5] Traditionally, change patterns are broken down as radical vs. incremental, disruptive vs. evolutionary or continuous vs. discontinuous innovation (Abernathy and Utterback, 1978; Dosi, 1982; Grubler, 1998; Grübler, Nakicenovic, & Victor, 1999). Dosi distinguishes continuous from discontinuous types of technology change by noting that continuous changes are typically associated with advances along a technology trajectory of a larger technology paradigm, whereas discontinuous change are related more to the emergence of a new paradigm (1982).

Greg Unruh differentiates transition stages still further with a taxonomy that encompasses end-of-pipe (incremental), continuous (non-disruptive) and discontinuous change (disruptive) (2000 and 2002). The additional intermediary stage can be understood to be an enhancement or upgrade of the existing architecture, which repositions the prevailing technology trajectory along a more sustainable pathway (Ibid, Berkhout, 2002). While bridging legacy and novel technologies, this method maintains inherent limitations, since nothing is fundamentally changed about the technology or the institutions themselves (Berkhout, 2002)

Frank Geels and Johan Schot articulate technology change from a structural perspective with transformation, reconfiguration, substitution, and realignment/ dealignment (Geels and Schot, 2007). While the above models of technology transition

Incremental change implies slight modifications to existing technology, like the addition of a catalytic converter to an automobile, whereas disruptive change refers to substantial adaptations in one technology or the case where one technology supplants another. The emergence of automobiles constitutes a form of disruptive technology by replacing carriages and opening new directions for use. Joel Mokyr posits that incremental and disruptive changes are not mutually exclusive, but can overlap, as most macro-inventions (disruptive changes) build on the accumulation of micro-inventions (incremental change) (Ibid).

Traditionally, technology change has been studied in neoclassical economics with an emphasis on (1) the relationship between supply and demand, (2) performance in production for which technology is an input, and (3) research and development, yet these do not account for the unplanned and less precise elements of development (Mokyr, 1990; Nelson and Winter, 1982; Mytelka and Smith, 2001).[6] Evolutionary economics provided a critical point of departure for understanding technology change by articulating how natural selection and competition may be key drivers, rather than profit maximization and market equilibrium as found in neo-classical economic theory

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are descriptively useful in focusing on the intensity of systemic disruption, Geels and Schott's approach offers a more distinct calibration of the means of change. All ultimately add to the specialized vernacular which informs approach to green technology scale-up.

[6] According to the neoclassical economics school of thought, technology is viewed as an intermediary factor in relation to the basic factors of production: labor and capital (Hadjilambrinos, 2000). Technology change then derives from the need to improve resource utilization (Ibid, citing Cohendet et al, 1991; Gilbert, 1985; Moroney and Trapani, 1981).

(Nelson and Winter, 1982). When combined with ideas from the emergent, cross-disciplinary field of innovation (Fagerburg, 2005), this reconceptualization emphasizes non-linear, technological development in which certain interactive or cyclical interactions explain important technological shifts (Mytelka and Smith, 2001; Fagerburg, 2005).

Innovation

Innovation or adaptation to improve performance and/or quality can factor in the development of energy systems. Classic views of innovation highlight a linear framing where technological development occurs in three stages: (1) invention, when an idea first emerges; (2) innovation, the first practical application of the invention; and (3) diffusion, when the innovation is dispersed widely for use (Schumpeter, 1975/1942). More recent views of the innovation life cycle map the inception of an idea and its incubation through testing and prototyping to niche market development and finally to widespread diffusion with feedback loops, links and overlap throughout the cycle (Grubler et al, forthcoming; Kline and Rosenberg, 1986; Nakicenovic et al, 1998/1999). Both models describe processes which principally occur in institutional settings, yet there is a growing awareness that innovations and the agents of such change extend beyond industrial laboratories and academic settings (Lundvall, 1988 and 2010; von Hippel, 2005 and 2010), and do not need to be rigorously sequenced (Sovacool and Sawin, 2012). This study presupposes that innovation cannot be reduced to an explicit series of procedural steps. It is an improvement which enhances the quantitative or qualitative use of energy, including the sourcing, conversion, application and use, distribution, final disposal, etc. This includes changes which improve the energy system in less overt ways, such as with its governance and financing.

Theoretical writing on innovation in the context of national systems, called national systems of innovation (NSI/NIS), emphasizes interactions of drivers within a country that produce systemic feedbacks and constructive adaptations in the advance of a technology (Edquist, 2005; Freeman, 1987; Nelson 1993; Lundvall, 1992; Ridley et al, 2006). This body of theory recognizes that shared language, culture and institutions at the country-level can serve to frame important conditions for innovation systems. Richard Nelson and Bengt-Åke Lundvall developed two primary lines within NSI literature. Richard Nelson's applied analysis centers on the role of national R&D systems (Edquist, 2005, citing Nelson, 1993). Somewhat differently, Lundvall's more theoretical NSI approach underscores the role of learning, user-producer interactions and the home market for economic specialization (Edquist, 2005; Lundvall et al, 2002).

Recognizing the relevance of the national lens in NSI, this study adopts a wide view of innovation. Going beyond some the more ordered models, like those described above, it recognizes that developments can arise from a change in technology; products; processes or practices tied to learning and experimentation, serendipity, breakthroughs, etc from any sector in society. Synthesizing earlier ideas on MLP and TEP theory with writing by John Hughes on socio-technical systems, this study also acknowledges that systems of innovation occur in a web of technical, political, economic, and social factors (Hughes, 1987; Sovacool and Sawin, 2012; Freeman et al, 1982; Dosi et al, 1988;

Perez, 1985, 2002, and 2004a; Geels, 2004 and 2005; Geels and Schot, 2007; Freeman and Louca (2001).

F. PACE and TIMING

What is commonly understood about the pace of technology change is that first adopters, generally by virtue of novelty and learning, often progress at a rate that is slower relative to late adopters (Grubler 1996, 1998, 2008; Grubler et al, 1999). Additionally, macro-level transitions may take numerous decades, if not longer (Ibid).

Cesare Marchetti and Nebusja Nakicenovic analyzed global primary energy substitution with logistic equation modeling in the 1970s, finding that the typical length of time to shift from one energy technology to another is 50-100 years (Marchetti and Nakicenovic, 1979). Arnulf Grubler later expanded on this analysis, positing that (1) the rates of change for global primary energy substitution have dramatically slowed since the mid-1970s, and (2) that early adopter countries reach a higher market saturation level, while later adopters convert (i.e. scale up) more rapidly but not as extensively (Grubler, 1996; forthcoming; see also Wilson, 2009; Wilson and Grubler, 2011). Such thinking complements ideas which view early adopters as having opportunities to define the dominant technological design during a formative period, as well as to gain early market share – deemed crucial in industrial development.

Jose Goldemberg considered early and late adopters in the context of leapfrogging. He contended that later adopters, like newly industrializing countries, have an opportunity to sidestep issues associated with early use by advancing to next generation technologies (Goldemberg, 1998). Essentially, late adopters are not encumbered by infrastructure and sunk investments of first movers, so may benefit from prior learning to advance directly to newer, more superior technologies.

Daniel Kammen points out that leapfrogging is one (but not the only) way to replace 'locked-in' technology. Hybridization is another means in which the new and old technologies are used concurrently, allowing continued learning and refinements to new technologies as older ones are sustained (2004). An illustration of this is can be found with developments in steam and gas-powered generators during the 20th century. Early successes of steam technology in the power sector could have led to a full phase-out of gas turbine technology. Nonetheless, gas turbine technology continued to advance independently in the aviation industry with later spillovers into the power sector. Eventually, gas turbine technology became the main component of the hybridized combined-cycle system in power generation (Ibid).

Kammen also notes that market transformation, which may include public sector funding, is necessary to assist with the commercialization of clean energy technology (Ibid). This recognizes two primary rationales for a government to intervene with clean energy technology, namely that traditional energy prices do not account for social costs or other externalities, and that private firms are unable to appropriate the benefits of pre-commercialization investment. Going further, Kammen indicated that the social rate of return on R&D is greater than private returns, so private firms may be less inclined to invest to increase social welfare (Ibid). Here, public support may be justified with wide-ranging spillovers from clean energy technology advances.

The pace of diffusion for new technology is often represented in the S curve, an widely used model reflecting rates of dispersion at different points of a technology's uptake (Abernathy and Utterback, 1978). In simple form, the model shows that adoption begins slowly, then turns to more rapid uptake as acceptance or favorable interests spur momentum. The process reaches a tapering off point, often seen as saturation. The changing rates of diffusion are characterized by different slopes in the contours of the S curve.

Focusing more squarely on the influential factors of diffusion rates, Everett Rodgers theorized that the pace of change depends on:

- Relative advantage of a change in economic, social and environmental terms vs. the status quo it supersedes;
- Compatibility or coherence of change with norms, needs and understanding;
- Complexity of a change;
- Opportunities for testing a change; and
- Observability or clarity of positive results (Rogers, 1995; Sawin, 2002).

Perceived difficulty or complexity of change, for example, appears to be negatively associated with the rate of adoption (Rogers, 1995). Grubler, Nakicenovic and Victor developed this idea somewhat differently by differentiating between factors which slow or accelerate transitions. Factors which slow diffusion include market size (larger markets require more time), technology complexity, and infrastructural needs (1999b). Conversely, factors which can accelerate diffusion include the pre-existence of niche markets which allow early testing, and the comparative advantage of the new technology in areas such as performance, efficiency and costs (Ibid; Grubler, forthcoming). While these ideas warrant further study as they relate to energy transitions, a reasonable consensus exists among technology diffusion writers that determinants of transition rates can differ over time (Grubler, 1997, and Rogers, 1995).

Niches and enabling environments can also influence innovation and diffusion. Niches, as noted with multi-level perspective theory-building, are spaces where innovations incubate in protected form. Somewhat differently, an enabling environment refers to exogenous forces or conditions which shape the adoption of a technology (Nelson and Winter, 1982; Aguayo, 2008). Institutional landscapes and societal acceptance are co-existing elements of such enabling environments.

An institutional playing field, like a market, is a societal construct where technology innovations must locate. These playing fields are often riddled with latent or socially embedded forms of incumbency that constrain entry opportunities for novel technologies (Schumpeter, 1975; Hargadon and Douglas, 2001). To overcome such encumbrances, innovators must position disruptive ideas in the familiar, locating advances within recognized institutional frameworks, like routines, while also favorably distinguishing the new entrant from incumbent technologies (Hargadon and Douglas, 2001). Electric street lights of the late 1800s illustrate this concept. When first introduced, electric lights were designed to look like traditional gas lamps. Once electric lights became established in everyday use, the gains from their use eventually led to the supplanting of incumbent technology (Ibid).

Like niches and enabling environments, clusters and spillovers can affect the timescales of technology change. Clusters are groups of inter-related technologies or industries, which emerge and co-evolve together. Such development is evident in the overlapping development of the internet, wireless computing, and social communication technologies (Ausubel, 1991, Porter, 1998, Freeman and Perez, 1988). While clusters and spillovers are generally viewed as signs of industrial growth and technological development, there isn't a consensus on whether their presence accelerates or slows the pace of change for the original technology. What is likely for energy system change is that such clusters and spillovers improve the durability of change, since these developments are mutually reinforcing (Landes, 1969; Porter, 1998).

G. LEARNING and ADAPTIVE CAPACITIES

Technology change writers often point to the truism that learning and adaptiveness are crucial for development, yet more can be said about the type of and access to knowledge.[7]

[7] See Fagerberg, 2005; Mytelka and Smith, 2003; Mytelka and Goertzen, 2004.

Scholarship on technology, economics, industry and the environment raises a fairly consistent theme that learning associated with tacit or local knowledge can strengthen overall development, but nonetheless may be missed (Backstrand, 2003; Fischer, 2000; Lester and Piore, 2004; Lundvall, 1988, 2010; Von Hippel, 2005). End-user experiences with the performance of certain technologies, like wind turbines, will be shown to be an important form of local knowledge contribution in Chapter 5.

When contemplating learning and innovation, it is also worthwhile to note how access to knowledge can also be a critical component. Economist and historian of technology change Joel Mokyr, for example, argues that it wasn't inventors or socio-economic factors which drove the Industrial Revolution, but rather people exchanging knowledge (2002). This instrumentality of access complements another point in innovation writing on feedback loops that highlights the significance of multi-directional knowledge flows among producers and users of technology to enable progress (Von Hippel, 2005; Lundvall, 2010; 1988).

As with knowledge and feedback loops, the adaptive capacity of countries is another way to conceptualize national energy trajectories. Energy historian Vaclav Smil studied energy system transitions, concluding that the adaptive capacity or nimbleness of a country factors in the pace of its energy system conversion (2010). Using the discovery and adoption of North Sea natural gas by the United Kingdom versus the Netherlands as a comparative example, Smil argued that the Netherlands was able to convert its energy system more quickly to gas usage than the United Kingdom. because it was less encumbered by an established infrastructure and thus more nimble to adapt (Ibid).

A variant on adaptive capacity was articulated by Michael Porter in writing on the competitive advantage of nations. Here, Porter indicated that countries are more likely to succeed with domestic industries, if system determinants (i.e. supporting industries, internal conditions, and firm dynamics) are more favorably disposed to development (1990). This idea was expanded with the notion of national innovative capacities (NICs), which indicates that a country's enabling environment, the factors that shape its innovative propensity, and the links between these two elements define its NIC (Furman et al, 2001; Henderson and Newell 2010/2011; Porter, 1998). Since national energy transitions are on some level about a country's capacity to adapt, these concepts will inform the analysis which follows.

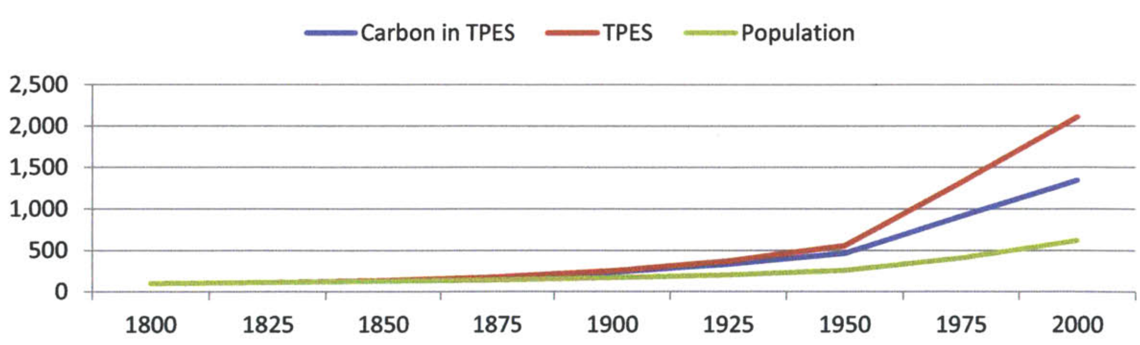
In a related line of thinking, Joel Mokyr contemplated different levels of monopoly and competition vis-a-vis technology change, questioning whether certain market structures are more conducive to innovation (1990). The underlying logic, here, is that specific market structures might not only affect the innovative propensity of an industry, economy or society, but there may also be reshaping of a market structure through two-way channels (Ibid). In 1990 analysis of this subject, Mokyr found that much of the modern empirical literature is inconclusive and at times contradictory on this front (Ibid).

A more quantitative means to evaluate learning is with experience or learning curves, introduced for the early aircraft industry[8] to provide context to cost improvements. These curves, typically represented as double log functions, evaluate the change in costs for every doubling of output or installation (Wene, 1999; Neij, 1997; IEA, 2000). If, for example, the rate of cost improvement is 10% with the doubling of quantities, then the experience or learning rate is 90% (or 100-10 = 90) (IEA, 2000). When possible, learning curves are employed in the analysis which follows.

H. CARBON-ENERGY TRENDS

Carbon is a defining attribute for fuel types in this research. Since 1800, the total carbon emissions from global primary energy have increased ~6% per year as total primary energy use rose ~10% per year (Figure H1).

Figure H1: Patterns in Carbon Emissions of Total Primary Energy, Total Primary Energy, and Population Growth, (Indexed to Base Year 1800)



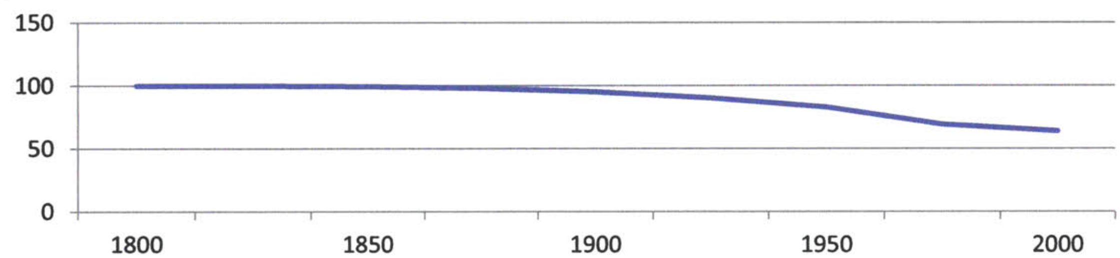
Source: Grubler (2008a).

[8] This form of analysis is traceable to a 1936 article on airplane assemblies (Wright, 1936).

This absolute growth in carbon from fossil fuel combustion matters as it is increasingly recognized to be a primary determinant behind the radiative forcing in climate change (IPCC, 2007). Together with the rise in other GHGs, it has led international bodies to call for substantial reductions in carbon intensive energy (Ibid; IEA, 2011). As data accrues and debate persists (Herath, 2011), it is useful to note some distinctions in the trends.

In contrast to the rise in carbon evident in Figure H1, Figure H2 shows the carbon intensity of global primary energy (i.e. the level of carbon emissions released per energy unit of output) decreasing 36% overall or <0.2% per year in the past two centuries.[9]

Figure H2: Carbon Intensity of Global Primary Energy
(Tons of Carbon per EJ, Indexed to Base Year 1800)



Source: Grubler (2008a).

[9] Carbon intensity can also be gauged as carbon per unit of GDP and per capita which complicates discussions over carbon reductions.

The Kaya identity expresses CO_2 emissions as the product of the carbon intensity of energy (CO_2/E), energy intensity of economic activity (E/GDP), economic output per capita (GDP/P), and population (P):

$CO_2 = (CO_2/E) * (E/GDP) * (GDP/P) * P$ (Kaya, 1990).

This decline is explained by the faster growth rate of energy use in relation to the rate of carbon emissions from energy use. This decoupling of energy and carbon patterns occurs with the successive introduction of less carbon intensive fossil fuel sources from coal to oil to natural gas in which a higher hydrogen to carbon ratio is evident in the fuels (Gibbons and Gwin, 2009; Grubler, 2004, citing Marchetti, 1985).[10] This decoupling is also amplified by the introduction of nuclear energy and increased use of renewables in the latter half of the 20th century (see Chapter 1, Figure E1). As global energy demand is projected to increase 50% by 2035 (BP, 2011; IPCC, 2007; IEA, 2011d and 2011e; EIA, 2011), the choice of fuel type clearly can impact the carbon trends.

I. ADVANCING CHANGE

There is a saying that great opportunities are often disguised as insoluble problems. While no fuel is without challenges in its utilization, heavy reliance on fossil fuels will test the bounds of dependence. It is here is where levers, actors and strategies merit some consideration.

Levers of change

Levers of change receive a fair amount of attention in policy discussions. Over the years, policy writers have put forward various tool typologies, including: Hood's NATO

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[10] The hydrogen-carbon ratios or H/C for various fuels are: coal (0.5-1:1), oil (2:1), natural gas (4:1).

breakdown;[11] Salamon's more contemporary, governance framework;[12] and Bemelsmans-Videc, Rist and Vedung's simplified regulations-economics-information model (2005). Such frameworks offer different rationales for organizing the way to think about policy. Irrespective of how one classifies the policies, the optimization of policy tools arguably depends on an effective matching of such instruments with conditions and aims.

In Chapters 4-8, policy tools and broader approaches are assessed in terms of the extent and form of government intervention. Examples of robust intervention include direct deployment, procurement requirements which guarantee a market, and renewable portfolio standards which obligate a utility to derive a portion of its fuel mix from renewable energy. By contrast are policy measures which rely less on intervention and more on encouraging voluntary action, such as with investment credits which allow tax write-offs for specific capital purchases.

Another way to consider levers is with respect to potential for effectuating change.[13] A window of opportunity emerges, according to some policy writers, when various socio-

[11] NATO centers on governing resources, which include nodality (central information), authority, treasure (finance), and organizations, like state-owned enterprises) (Hood, 1968).

[12] This assumes that government can adequately function beyond a centralized bureaucratic state through coherent collaboration with third parties (Salamon, 2002).

[13] Other policy instrument criteria could include elements like the simplicity of policy design; feasibility of implementation; economic efficiency; political palatability; the timing of anticipated outcomes; fairness; etc.

political streams converge (Kingdon, 1995; Zahariadis, 1999). Here, an advantageous period for action may appear, if a country encounters challenges over rapidly rising energy import prices and unemployment amidst rising interest in the environment.[14] Whether such circumstances emerge or are prompted, they test the readiness of a country's markets, institutions, social contract, expert capacity and infrastructure.

Agents of change

As with levers of change, the role played by actors can be pivotal for outcomes. Policy writers describe 'entrepreneurs,' 'champions' and 'fixers' as those within processes or organizations who go beyond their spheres of responsibility to act and meet a larger interest (Kingdon, 1995; Bardach, 1977; March and Olsen, 1989). Innovation writers Peter Karnoe and Raghu Garud amplify on this idea. Unlike path dependency writing which generally relegates human agency to passively ride out the flow of events, Garud and Karnoe and others offer an alternative whereby entrepreneurs navigate the flow of events as they constitute them (Garud and Karnoe, 2001, citing Schumpeter, 1942,

[14] This study recognizes that there are different lenses for understanding national level outcomes, as noted in Graham Allison and Philip Zelikow's seminal work in international relations and policy theory (Allison, 1969; Allison and Zelikow, 1999). In the rationalist school, developments can be viewed as reflecting an intelligent and rational set of actions, irrespective of changes in people, administration approaches, etc (Allison, 1969, citing Morgenthau, 1960). By contrast, other schools of thought view outcomes based on organizational process or bureaucratic politics (Allison, 1969; Allison and Zelikow, 1999).

In a related vein, segments of energy trajectories can reflect a single, instrumental decision or countless, smaller ones. Such understanding resonates with lines of inquiry in international relations, organizational and social theory which merit further exploration in the context of energy transitions (Allison, 1969; Giddens, 1979 and 1984; and Weber, 1947 and 1958).

Hayek, 1948; Weick, 1979; Astley, 1985; Rao and Singh, 2001). Such entrepreneurs have a capacity to mobilize and actively shape paths, despite resistance and inertia. Complementing Joseph Schumpeter's thinking on creative destruction,[15] Garud and Karnoe point out that entrepreneurs may purposefully deviate from existing order in the interest of creating new futures. This study recognizes active and passive agents of change. An active agent, as the name implies, engages directly in effectuating change. Somewhat differently, a passive agent is less direct, indicating a desire for change, for example, which catalyzes others into action.

The constellation of sectoral actors typically includes government, industry and civil society. A government is often cast as the actor which protects the public good in areas which would otherwise not be met (Hobbes, 1996, Olson, 1965; Cowen, 2002; Medema, 2007). Industry is then typically represented as the engine of growth with backward and forward linkages or ties to other industries and areas of society (Chakravarty and Mitra, 2009; Nurse, 2007; Bogliacino and Pianta, 2011; U.S. Department of Commerce, 1995; Treganna, 2007). Civil society is generally understood to be people in the domain of life outside of the other sectors (UN, undated; Mann, 1984; WACP, undated).[16] In

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[15] The concept of creative destruction, as it relates to innovation, emerged with works, like Schumpeter's Business Cycles (1939) and Capitalism, Socialism and Democracy (1942). The idea refers to the transition which occurs with disruptive innovation, as incumbent players or technologies cede some monopolistic control to new entrants.

[16] The meaning of civil society has evolved with writing on political philosophy and the nexus of society and the state by: Plato, Cicero, Hobbes, Locke, Rousseau, Hegel and de Toqueville, among others. Currently, there is no universally-accepted definition.

scholarship relevant to energy transitions, civil society is often mentioned in terms of acceptance, effects, and practices.[17]

Importantly, participants in energy system change can also go beyond the above, more simplified groupings to include intergovernmental organizations (IGOs), non-governmental organizations (NGOs), and coalitions of boundary-spanning actors.[18] Actors like state-owned enterprises, which bridge government and industry (Marcel, 2005; Stevens, 2003), will prove to be some of the more pivotal in the cases which follow. Among these more nuanced groups, potential exists to leverage cross-sectoral strengths, yet competing aims and organizational dissonance can also make for much more complex terrain to navigate.

Sources of Change

When considering any sort of national change, policy, diffusion and development writing often points to top-down and bottom-up approaches as primary means for rolling out initiatives (Howlett et al, 2009; Helm, 2007; Perez, 2004b; Rogers, 1995). The top-down approaches are often characterized as being governmental initiatives which include:

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[17] See Bell et al, 2005; Darby, 2006; Devine-Wright and Devine-Wright, 2006; EC, 2007; Geels, 2005; Golay, 2001; Hess, 2007; Hohmeyer, 1988; Horst, 2008; Jackson, 2005; McMakin et al, 2002; Parrish, 2008; Ornetzeder and Rohracher, 2006; Smith, 2006; Wüstenhagen et al, 2007.

[18] IGOs are entities that are generally established by treaty and are composed of sovereign, member states or other international organizations. The World Bank, Intergovernmental Panel on Climate Change, and the International Renewable Energy Agency are examples of this. NGOs are, broadly speaking, advocacy or service-driven entities that are run beyond the direction of government and generally do not generate profits. WorldWatch and the Red Cross are some of the more well-known examples.

centralized planning, standardized implementation, mandates, and/or limited (if any) public engagement. Bottom-up approaches may have a decentralized nature, include greater engagement of citizens and/or non-governmental groups, and be effectuated by non-regulatory means, including new societal rules and institutions (Ostrom, 1990) or market-based options (Lindblom, 2001). In this study, the top-down/bottom-up approaches are explicitly differentiated by the extent to which the national government intervenes to effectuate a change.

J. CONCLUSION

Accelerating change, particularly through innovation, is now regularly invoked as the solution for sustainability issues, yet diffusion research indicates that large-scale adoption and substitution of new energy technologies can take 50-100 years or more. Major elements which appear to shape the pace include the compatibility or coherence of the specific change with norms, needs and understandings; the complexity of the change; and infrastructural needs. As these and other determinants of change come into play, diffusion writing underscores how these factors themselves can vary over time. It is at this juncture where case analysis offers empirical depth to these ideas.

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Chapter 4:

Brazilian Biofuels: Distilling Change

Ethyl alcohol is the fuel of the future. - Henry Ford, September 20, 1925[1]

A. INTRODUCTION

In April 2010, the 'Green' Hornet', a navy fighter jet, publically demonstrated a flight at 1.7 times the speed of sound with a 50:50 mix of biofuels and aviation gas (Chambers and Yetiv, 2011). The jet was part of a plan to retool the United States navy's energy strategy, which included certifying the entire air and surface fleet to use biofuels (C-Span, 2012). Such measures could be viewed as representing the vanguard of development in a world where biofuels now equal only about 3% of total transport fuel on an energy basis (IEA, 2011). Yet studies show that biofuels could provide 27% of all global transport fuels by 2050 with fuel switching for jet fuel, diesel fuel and kerosene in particular (Ibid).[2] The case of the Brazilian biofuels transition offers key lessons on adopting low carbon energy in transport at scale.

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[1] "The fuel of the future is going to come from fruit like sumach ... or apples, weeds, [s]awdust – almost anything. There is fuel in every bit of vegetable matter that can be fermented." Kovarik, 1998, citing Henry Ford in the New York Times, September 20, 1925

The Ford Model A car (1896) used pure ethanol (Banco Nacional de Desenvolvimento Economico e Social /BNDES and Centro de Gestao de Estudos Estrategicos/CGEE, 2009).

[2] This would entail roughly 65 EJ of biofuels feedstock and 100 million hectares of land in 2050 (IEA, 2011).

Known as a historical leader in biofuels, Brazil is the only country to have substantially altered its transport fuel mix with biofuels at scale in unit and relative terms (IEA, 2011; Kojima and Johnson, 2005; OECD/IEA, 2010b). In 1970, roughly 1% of Brazilian transport fuels were ethanol, a form of biofuel (Ministério de Mines e Energia/MME, 2011). Today, 17% of all Brazilian transport fuels and roughly 41% of Brazilian automotive fuels are ethanol (Ibid).[3] Brazil's leadership in biofuels extends to its long-term production and export history, equaling 31% of the global ethanol supply in 2010 (REN21, 2011; MME, 2011; Timilsina and Shrestha, 2010; Rocha, 2009). It has the lowest production costs for ethanol (IEA Bioenergy, 2011). There are essentially no light-weight vehicles in Brazil now running on pure gasoline, as gasoline has been blended with 10-25% ethanol since 1976 (Andrea Puerto Rico, 2008).[4] Brazil also has a unique distribution network in which 37,000+ fuel stations offer E25 blends of fuel with 25% ethanol and roughly 35,000 have E100 or complete ethanol (OECD/IEA 2010b, citing MME 2009).

This chapter explores the way Brazil adapted its sugar and automotive industries, along with its fuel distribution chain to establish a comprehensive, national market and

[3] Automotive fuels, for the purposes here, consist of gasoline and ethanol. Transport fuels include those used in rail, sea, aviation and heavy road vehicles in addition to those used for automobiles.

[4] This is required by law since 1993 (Lei N° 8.723).

technologies centered on biofuels. Strengths of top-down and bottom-up led change will both be seen, as well as the significance of "dual use" technology.[5]

The chapter begins by discussing characteristics of biofuels, automotive and bioelectricity technologies. It then offers a broad overview of the Brazilian biofuels transition, followed by significant innovations and determinants in the energy system transition. Change indicators for the energy mix, costs, social acceptance and aspects of industrial development are then discussed with concluding takeaways.

B. BASICS OF BIOFUELS, AUTOMOTIVE AND BIOELECTRICITY TECHNOLOGIES

To appreciate the opportunities for scaling biofuels, one should first understand fundamentals of biofuel science, automotive technology and bioelectricity.

Biofuels

Biofuels are transport fuels produced from agricultural or other biological feedstocks (Seelke and Yacobucci, 2007). The two, most common forms are ethanol and biodiesel which are often blended with petroleum-based fuels, but which can also be used independently (REN21, 2011; Schnepf, 2010). Ethanol, also called ethyl alcohol, is a fuel derived from the fermentation and distillation of sugar or starch-based biomass (i.e. plant material), including sugarcane, corn, cereals, etc (REN21, 2011; IEA, 2007; Yacobucci, 2007). By contrast, biodiesel is made by chemically reacting alcohol with

[5] Dual use implies there is more than one purpose or critical function for a technology or process.

lipids from vegetable oils, animal fat, or from recycled cooking oil to produce fatty acid esters (Seelke and Yacobucci, 2007; IEA, 2011).

The primary form of biofuel examined in this chapter is ethanol which contains the same chemical compound (C_2H_5OH) as that in alcoholic beverages (Yacobucci, 2007). It may be used in standard internal combustion engines as an anhydrous additive or with modified vehicles as a stand-alone fuel in hydrous form. Hydrous ethanol is an ethyl alcohol with a maximum water content by mass of 6.2-7.4% that differs from anhydrous ethanol which has less than 0.6% water (Banco Nacional de Desenvolvimento Economico e Social /BNDES and Centro de Gestao de Estudos Estrategicos/CGEE, 2008). Hydrous or hydrated ethanol is used in ethanol-only vehicles, dubbed neat vehicles, or in certain flex fuel cars, such as those marketed in Brazil (see Automotive section). The water content of ethanol must be limited when blending with gasoline, since its presence impairs the capacity of ethanol and gasoline to mix without separation (miscibility), particularly in cold weather (Joseph Jr., 2010).

Production of ethanol from sugar-based feedstock, like sugarcane, sugar beets or molasses, generally entails:

(1) the processing of feedstock to separate fermentable sugars;

(2) the addition of yeast to trigger fermentation; and

(3) distillation of the resultant alcohol – producing a hydrous ethanol (Seelke and Yacobucci, 2007).

If the product is to be used as an additive in gasoline, the hydrous ethanol is then dehydrated with a second stage of distillation through the addition of a co-solvent to become an anhydrous ethanol (Ibid; Joseph Jr, 2010). The production of ethanol from starch-based feedstock, like corn and cassava, requires an additional step -- the hydrolysis of starch into glucose which breaks the starch into fermentable sugar (saccharification) (Kojima and Johnson, 2006; IEA, 2011).[6]

Biodiesel is a fuel that can be used in diesel engines without adaptation (EIA, 2012). The most popular way to produce biodiesel is through a process of trans-esterification which converts a base oil to an ester with an alcohol, like methanol, ethanol or butanol, when presented with a catalyst (Coelho and Goldemberg, 2004). Feedstocks can include vegetable oils, like rapeseed or soy – the two most prevalent - as well as jatropha, coconut, palm, and flax, among others.[7]

The IEA indicates that Brazilian sugar-cane based ethanol has one of the highest energy yields among biofuels, using about 10-12% of ethanol's final energy to generate the ethanol. This contrasts with biodiesel and ethanol from cereals and corn which use 30% and 60-80%, respectively (IEA, 2007). In terms of price, Brazilian sugarcane-based

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[6] Production costs are influenced by feedstock (IEA, 2011). Processing of ethanol from starch-based feedstock requires more energy than that from a sugar-based feedstock (Ibid). Costs for starch-based fuel are also influenced by the value of co-products, like dried distiller's grains with solubles and fructose (Ibid).

[7] Prior to conversion, these oils may be previously unused or recycled from cooking use. Animal feedstock includes fats from cattle, poultry and pigs, as well as fatty acids from fish oils. Other feedstock from sewage and sea farming is also being explored (King, 2006; Glenn et al, 1998).

ethanol is competitive with oil selling at roughly $40-50/barrel (Ibid). For comparison, Brent crude oil prices in 2011 averaged $100+/barrel (EIA, 2012). The substitution value for ethanol relative to gasoline is discussed below with Automotive Technology.

Debate exists over how to classify biofuels. Distinctions, for example, can be made by technology maturity, GHG emission balances, or feedstock (IEA, 2011). This study uses feedstock and technology maturity as points of references. In recent years, research has increasingly focused on new feedstock, like algae and fibrous materials (i.e. perennial grass) to produce cellulosic ethanol. These encompass what are sometimes referred to as advanced biofuels, which are not widely commercialized. The current case focuses almost exclusively on sugarcane-based ethanol, since it represents the majority of the Brazilian transport sector's low carbon energy. Other forms of biofuels, namely biodiesel, are noted, where relevant.

Environmental and Food-related Considerations

Biofuels have a mixed record in terms of the environment. Their use can reduce the amount of pollutants emitted relative to those produced by gasoline or diesel combustion (Seelke and Yacobucci, 2007), yet the types of resources and processes used, as well as safeguards, have different GHG effects (Bracmort, 2012; Yacobucci and Bancourt, 2010; REN21, 2010; Lee et al, 2008). Recent studies indicate that consumption of corn-based ethanol can result in 13-22% less GHG emissions compared to that from gasoline, while GHG emissions from sugarcane and cellulosic ethanol may be 56%-90% less than gasoline (Seelke and Yacobucci, 2007; citing Farrel et al, 2006; US EPA, 2007).[8] However, greenhouse gas accounting for biofuels and biomass is being reconsidered as forms of land use, agricultural practices, and feedstock vary widely with respect to the level of associated emissions (REN21, 2010; Lee et al, 2008; IEA, 2011; Berndes et al, 2010; European Community/EC, 2010). Particular concerns relate to with biofuels produced with new land clearing, use of nitrogen-based fertilizers, slash and burn harvesting techniques, and substantial transport to distilleries, since each enlarges the release of CO_2 emissions in relation to corresponding processes which do not (Ibid; Campeon and Polenske, 2011; US EPA, 2007).

The food vs. fuel debate is another consideration for biofuels and the environment which drew attention following an agricultural commodity price boom between 2006 and 2008 (World Bank, 2010; IEA, 2011). Fundamentally, the concern is based on the notion that land conversion for fuel crops may displace food-based crops, in turn leading to higher food prices (Runge and Senauer, 2007; Earley and McKeown, 2009; Yacobucci and Schnepf, 2007; Lee et al, 2008). Recent analyses by the World Bank and Fundacao Getulio Vargas indicated that a variety of factors contributed to grain price increases, including high oil prices, poor harvests, and financial investor speculation – more so than biofuel production (World Bank, 2010; FGV, 2008). Yet reports also show this may not be a concern for Brazil, as sugarcane fields for fuel production correspond to roughly 5% of cultivated land and 0.5% of the area of Brazil (BNDES and CGEE, 2008; Food and Agriculture Organization/FAO, 2008).

[8] EPA analysis considers the farm to tailpipe emissions plus direct and indirect land use.

In line with the above issues is the concern that biofuels feedstock crops may displace biodiversity-rich habitats, such as the Amazonian rain forest and savanna lands, or pastures for raising cattle (Macedo, 2005). Within Brazil, sugarcane production is done in the South-Central and Northeastern regions (89% and 11%, respectively), mostly at great distances from the rainforest and savanna (Interviews, 2011-2012; Gordinho, 2010; World Wildlife Fund/WWF Global, undated). Yet questions remain on whether ranching activity is displaced from the sugarcane regions, thereby migrating to new land in Northwestern forested regions. Such an issue of encroachment is an ongoing area of study (Interviews, 2012), however in the interim, signs are promising. In 2010, the U.S. Environmental Protection Agency reviewed ethanol reporting and satellite imagery of land use to appraise biofuels, like Brazilian ethanol, for certification of fuels in its Renewable Fuel Standard (US EPA, 2010; ICIS, 2010). Brazilian ethanol was classified as an advanced biofuel, meaning it meets a 50% greenhouse gas emissions reduction requirement (Ibid). The Brazilian Sugarcane Industry Association, UNICA, elaborated, indicating that sugarcane ethanol reduced such emissions by 61% relative to a gasoline reference case (ICIS, 2010).

Automotive Technology

Automotive technology which uses ethanol can be classed by categories including: standard, spark-ignition internal combustion; compression ignition; neat; and flex fuel technology.

1. *Spark-ignition internal combustion (ICE) vehicles* are the most prevalent on the roads today (Milligan, 2011). The engines are versatile and can run on fuels including oil, liquefied petroleum gas (LPG), ethanol and natural gas (Ibid). Among engine technologies, the ICE is one of the less efficient kinds for converting fuel to mechanical energy with automotive efficiencies at roughly 15-20% and a peak of 32% (Ibid, citing Wu and Ross, 1997). Its technology can use gasoline-ethanol blends generally up to 10% ethanol (E10) with no changes in materials, components or engine calibration (CGEE and BNDES, 2008; Everett et al, 2012; Interviews 2010-2012). With this technology, ethanol can serve as a fuel octane booster and reduce pollution, like that from tetraethyl neat and other oxidizing agents which are banned or being restricted (Ibid). In blended form, ethanol substitutes for gasoline on a one-for-one basis (Demetrius, 1990).

2. *Compression ignition, internal combustion engine vehicles* are generally heavy duty vehicles such as trucks, buses and trains (Milligan, 2011). The compression ignition attribute limits the fuel types that may be used to diesel, petrol, LPG, etc.[9] Its efficiency is generally 22-28% with an upper limit of roughly 43% (Ibid).

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[9] The characteristics which make ethanol suited for spark-ignition, internal combustion engines are not as conducive to compression ignition engines (diesel cycle) used in larger vehicles, like buses and trucks (BNDES and CGEE, 2008).

In the area of research, development and demonstration (RD&D), Sweden has adapted diesel engines with some success (Ibid, citing Sopral, 1983). Studies have also been done in Brazil to adjust fuel systems and integrate spark ignitions into diesel vehicles in order to utilize ethanol (Ibid). Such a breakthrough would be significant, as about half of Brazil's transport fuel is currently diesel-based (MME, 2011).

3. *Neat vehicles* are manufactured or adapted for hydrous ethanol and typically have a higher compression ratio of 12:1 relative to standard internal combustion engines that have a compression ratio of 8:1 (BNDES and CGEE, 2009; Goldemberg, unpublished). This is important since the compression ratio indicates the performance level of an engine. A higher ratio is advantageous, in that it allows more mechanical energy to be extracted from the air-fuel mix by an engine. Higher compression ratios however can also predispose engines to knocking (i.e. detonation), if lower octane-rated fuel is used. Knock sensors can mitigate against the reduced efficiency and engine damage associated with this.[10] When an engine runs on a higher compression ratio, it requires a richer air-fuel mix and more fuel, producing increased horsepower and torque (Gatti, 2010). Combining the higher compression ratio and lower energy content of ethanol relative to gasoline means roughly 1.25 units of pure ethanol replaces 1 unit of gasoline (Goldemberg, unpublished; Demetrius, 1990). In terms of technical change, neat vehicles require modifications in fuel-feed systems and the ignition to account for differences in the air-fuel relationship, in addition to changes to materials which are more compatible with ethanol (Ibid).

4. *Flex fuel vehicles*, also called flexible fuel (FF), use an internal combustion engine that is adapted to run with more than one fuel stored in the same tank. There are some indications that Ford Model T was the first flex fuel car (Kovarik,

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[10] See also http://en.wikipedia.org/wiki/Compression_ratio.

1998; Fuel testers, undated).[11] In the 1980s, this technology evolved in the United States, later advancing in Brazil (Gatti, 2010, citing Pefley et al, 1980; Joseph Jr., 2010). Flex fuel technology used in Northern hemisphere markets is primed to run with a blend of 15% gasoline and 85% anhydrous ethanol (E85) to allow for cold starts at temperatures below 11°C and to minimize low temperature ethanol emissions (Davis, et al 2000; Davis, 2001). Flex fuel technology used in Brazil allows any combination of gasoline with ethanol, as well as 100% gasoline or 100% ethanol. The technology differs from standard ICEs principally through a number of modifications to the fuel system and engine (US DOE, 2012a). Flex fuel technology is distinguished from dual-fuel technology that can also use more than one fuel, but which runs on one fuel at a time with each fuel stored independently in different tanks (US DOE, 2012b).

Generally speaking, utilization of ethanol as the stand-alone fuel or additive in spark-ignition, internal combustion engines has disadvantages related to ignition temperature and energy content, yet also advantages in cleaner combustion, engine performance and reduced emissions (BNDES and CGEE, 2009). One can contrast use of E100 and E22. A study with the VW Total Flex found power performance with E100 to be 3% higher and torque to be 2% higher, with fuel consumption at 30% higher (Joseph Jr., 2009).

[11] The Ford Model T had a low compression engine, adjustable carburetor, and a spark advance that enabled it to switch from gasoline to alcohol and kerosene (Kovarik, 1998). The drop in oil prices and limited alcohol supply during Prohibition enabled gasoline to emerge as the dominant fuel (English, 2008).

Octane Rating

Octane ratings measure the resistance of fuels to detonate and self-ignite (BNDES and CGEE, 2008). Ethanol is considered to be an excellent anti-detonating additive which can substantially improve the octane rating of a gasoline (Ibid).

Cold starts

Ethanol has a higher ignition temperature (420°C) relative to gasoline (220°C) (BNDES and CGEE, 2008, citing API, 1998 and Goldemberg and Macedo, 1994). Until advanced injection systems are developed, an auxiliary cold-start system is needed to start engines fueled by E100 in colder climates.

Exhaust Emissions

Combustion of hydrous ethanol or an anhydrous-gasoline blend produces less carbon monoxide (CO) and sulfuric oxides (SOx), hydrocarbons, and other pollutants relative to gasoline, due to the chemical composition of the fuels (BNDES and CGEE, 2008). By contrast, more aldehydes (R-CHO compounds) are produced and, depending on the engine attributes, nitrogen oxides (NOx) may also be emitted in larger quantities (Ibid). Concerns about aldehydes exist since they have carcinogenic potential, yet catalytic converters reduce these pollutants to accepted ranges (Ibid).

Other attributes of ethanol

In contrast to petroleum, ethanol is less likely to explode, less toxic if spilled, and has a more basic physical and chemistry profile to refine.

Bioelectricity

Bioelectricity (or biopower) refers to electricity derived from biomass. Sugarcane residuals, like bagasse (biodegradable and compostable fiber) and straw, are examples of biomass which hold roughly two thirds of the absorbed solar energy of the sugarcane plant (BNDES and CGEE, 2009; Goldemberg, 2010). Bagasse can be burned as a fuel in cogeneration-based processing employed in sugar and ethanol plants, enabling greater life-cycle energy efficiencies.[12] Straw is now also being utilized with the use of high pressure boilers.

C. ENERGY TRANSITION

Brazil is widely recognized as a leader in energy policy for reducing its dependence on foreign oil through increased oil production and domestic development of renewable energy sources (Meyer, 2011). This country which is 5th ranked for population and 7th for economy worldwide also has the oldest, most advanced, and most efficient ethanol program in the world (Budny, 2007). Brazil has the largest fleet of flex fuel vehicles (ANFAVEA, 2012c; UN Energy, 2011) employing technology that can be powered by any mix of ethanol and gasoline. Brazilian drivers can choose their preferred fuel - gasohol (gasoline and ethanol blend), ethanol or others - based on the relative prices at the pump (Almeida, 2007; Kamimura and Sauer, 2008; Meyer, 2011; Zarilli, 2006). In 2010, Brazilian drivers consumed 12,017 tons of oil equivalent/TOE of ethanol, an

[12] Cogeneration refers to the utilization of a power plant or engine in such a way as to generate electricity and useful heat.

increase of 303% on average per year since 1970 (MME, 2011). The following outlines the transition.

Historical Background

Ties between biofuels and engine technology can be traced to 19th century inventors.[13] However, for Brazil, signs of early developments are generally associated with the first part of the 20th century. In 1903, the First National Congress on Industrial Applications of Alcohol (I° Congresso Nacional sobre Aplicacoes Industriais do Alcool) recommended that infrastructure be developed to promote alcohol production and use (Goldemberg et al, 1993). In 1931, a 5% blending requirement was put in place for imported oil alongside guidelines for its transport and commercialization (Ibid; Decree 20,169).[14] Two years later, the federal government established an oversight body, the Institute of Sugar and Alcohol (Instituto de Acucar e Alcool/IAA), to regulate the sugar industry, promote alcohol fuel, provide technical assistance, and advocate for the small to medium-sized sugar industry actors in the Northeast (Gatti, 2010; Kovarik, undated; Demetrius, 1990). A comprehensive, national market for ethanol would not emerge until the 1970s, nonetheless the IAA would play a key role for the sugar-ethanol industry by

[13] Samuel Morey developed an engine that was powered by ethanol and turpentine in 1826 (Fuel testers, 2009). Nicholas Otto utilized ethyl alcohol in his early version of the internal combustion engine (Kovarik, 1998). Rudolph Diesel used peanut oil to fuel his first engine (IEA, 2011).

[14] In 1919, the Governor of Pernambuco, Brasil mandated that official vehicles run on alcohol (Kovarik, undated). By the mid 1920s and 1930s, alcohol was regularly blended with gasoline in a number of countries: Australia, Brazil (state level), Cuba, France, Germany, Philippines, South Africa, and the Scandinavian countries (Kovarik, 1998; CGEE and BNDES, 2008).

managing the planning and setting of supply targets, prices, and allowable export targets (Compean, 2009).

Brazilian research on biofuels in the early years was done by the Fuel and Mining Experimental Station (Estacao Experimental de Combustiveis e Minerios) which later became the ITA in 1920 (BNDES and CGEE, 2008; Ibid, citing Castro and Schwartzman, 1981; Figure C1). This research tested ethanol as a fuel for ICE engines in order to develop a technical knowledge base and support policies which would help to reduce gasoline imports (Interview, 2012).[15]

Figure C1: Vehicle Used for Alcohol Testing in early 20th Century Brazil

Source: Cruz, 2008.

[15] See also Kovarik, undated, citing "Brazil Seeks to Cut Gasoline Payments," New York Times, January 11, 1931.

Related research was done by Engineer Urbano Stumpf with the Aerospace Technical Center (Centro Tecnico Aeroespacial/CTA) in the 1950s-1970s, providing technical know-how for ethanol use and production of neat vehicles in the 1970s.

In the period leading up to the first oil shock, a number of key institutions were established, including the Cooperativa de Produtores de Cana-de-Acucar, Acucar e Álcool do Estado de São Paulo (Copersucar), Centro de Tecnologia Canavieira (CTC), and Programa Nacional de Melhoramento da Cana de Acucar (Planalsucar). Copersucar, a cooperative of sugar producers in the Sao Paulo region formed in 1959, was created to drive development in sugar, sugarcane and ethanol technologies, also addressing needs of the larger, Southern sugar industry actors that were not met by IAA (Copersucar, 2012; Demetrius, 1990).[16] Copersucar's research arm, the CTC, was established in 1969 to respond to the requests of producers and to conduct studies on plant breeding which were then extended to include all agricultural and industrial activity (Sorj and Wilkinson, 1993; Interview, 2012). In 1971, the Federal government created Programa Nacional de Melhoramento da Cana de Acucar (Planalsucar), a research program under IAA to conduct R&D on genetic improvement of sugarcane varieties (Ibid). This was done based on rationale that private research was not able to guarantee "a broad national perspective or adequate quality criteria" (Ibid). The national program was financed from a special governmental export fund and with experimental stations throughout the main sugar-ethanol producing states (Ibid).[17] Establishment of the two,

[16] Copersucar was incorporated in 2008 (Copersucar, 2012).

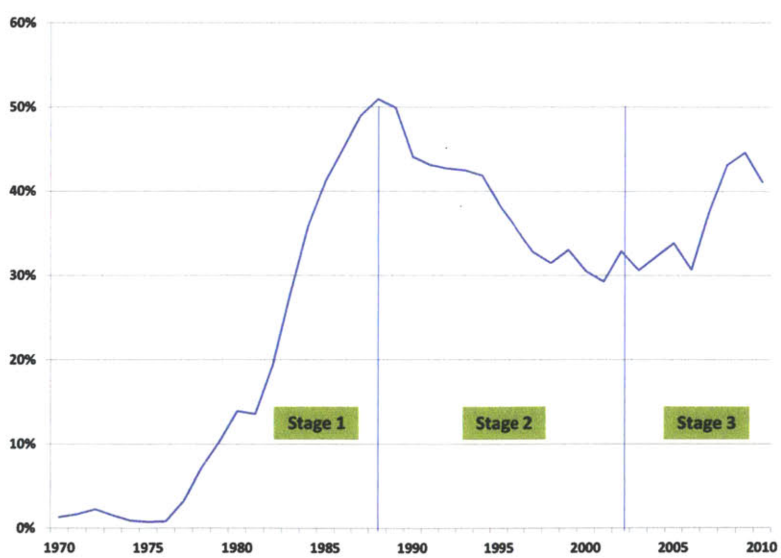
[17] See also http://pmgca.dbv.cca.ufscar.br/htm/pmg/histor.php.

latter institutions fostered some competition between public and private sector research and development on seed breeding, although the two appeared to differ somewhat in focus with the CTC focusing mainly on production in the state of Sao Paolo and the IAA focusing on all breeding areas in the country (Ibid; Matsouka et al, 2009).

Brazil's Modern Biofuels Transition: 1970 to the present

Ethanol had a minor foothold in Brazil's history until the 1970s when a full-scale, national market would emerge. The reconfiguring of industries and technologies enabled rapid substitution with ethanol and an ethanol-conducive automobile fleet. This Brazilian biofuels transition is discussed in three stages: 1970-1988, 1989-2002, and 2003-the present (Figure C2).

Figure C2: Stages of Brazilian Biofuels Development
(Share of Automotive Fuels)



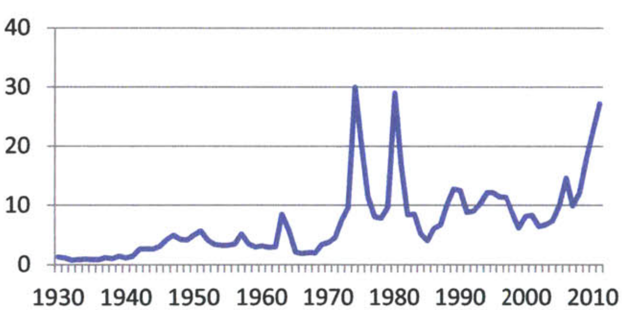
Source: MME data, 2011.

Stage 1: Accelerated Retooling (1970-1988)

The Brazilian biofuels transition emerged when conditions relating to the country's under-utilized sugar industry converged with the global oil shocks of the 1970s. The government oversaw a mobilization of industries with consumers responding.

In short, the privately-owned and publically-protected Brazilian sugar industry experienced a period of stagnation in the early 1970s linked to a decline in world sugar prices and period of investment (Figure C3) (Barzelay, 1986; Demetrius, 1990; Goldemberg, unpublished; Nunberg, 1978; Rosillo-Calle and Cortez, 1998; Schaffer et al, 2011). Attempting to revitalize its under-utilized capacity, the Brazilian sugar industry - namely Copersucar and the IAA – together with the Ministry of Industry and Commerce put forward what in today's time would be a stimulus plan, advocating increased domestic production of ethanol for use in transport

Figure C3: Nominal Sugar Prices (Cents per Pound)

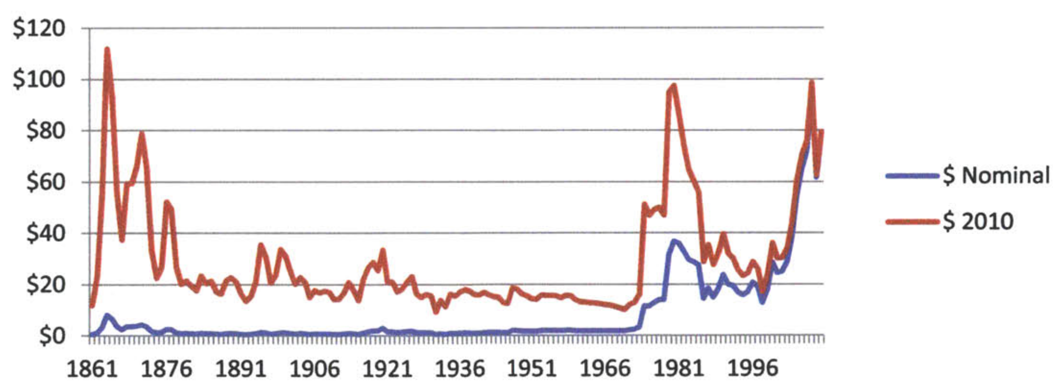


Source: Data from Nominal sugar prices – 1930-1959: International Sugar Council, The World Sugar Economy Structure and Policies: Volume II, The World Picture. 1963; 1960-1988 and 1989-2010: World sugar price (calendar year) USDA, Tables 3a and 3b, http://www.ers.usda.gov/Briefing/Sugar/Data.htm, citing New York Board of Trade https://www.theice.com/marketdata/reportcenter/reports.htm?reportId=10).

(BNDES and CGEE, 2008; Silva and Fischetti, 2008; Goldemberg, 2009 and unpublished). If implemented, the plan was designed to provide a cushion against sugar price flux that bring additional gains to the capital goods and the automotive sector (Demetrius, 1990).

As timing would have it, the global oil shock of 1973 provided key traction for the proposed plan. Brazil imported roughly 80% of its oil at the time (MME, 2011) when oil prices quadrupled from $2.90 to $11.65 between late 1973 and early 1974 (Figure C4). The import dependence altered the Brazilian trade balance from a path of equilibrium to a large and deteriorating deficit, accompanied by inflation (Ministry of Industry and Commerce/MIC, 1981; World Bank, 1981a; Goldemberg, unpublished). Between 1972 and 1974, the Brazilian oil import bill increased by a factor of 6 from $566 million to $3.2 billion (UN Comtrade, 2011, SITC Rev 1, Petroleum and Petroleum Products).

Figure C4: Historic Oil Price Flux: 1861-2010



Source: BP data, Statistical Review 2011. Note: 1861-1944 U.S. Average; 1945-1983 Arabian Light posted at Ras Tanura; 1984-2010 Brent.

It was during this time that extreme volatility played out in the global, sugar market with sugar prices dropping by almost a factor of 3 between 1974 and 1976, as oil prices nearly quadrupled between 1973 and 1974 (Figures C3 and C4).

Against this backdrop, President Geisel launched the National Ethanol Program (Programa Nacional do Alcool or ProAlcool) in November of 1975 (Decree 76.593; da Silva et al, 1978, citing Serra, 1976 and Serra et al, 1976; Demetrius, 1990; Hira, 2011; Goldemberg, unpublished).[18] Fundamentally, the aims of ProAlcool were to increase the domestic production of ethanol in order to better utilize spare, sugar capacity, reduce oil imports, bring some control to foreign exchange savings, and improve regional income disparities (Decree 76593; da Silva et al, 1978; CGEE and BNDES, 2008; Goldemberg, unpublished). With the ProAlcool Program, the government introduced a bundle of policies to radically alter automobile fuel usage and sourcing.

On the supply-side, the government established targets to achieve new ethanol production levels. With baseline production at 0.6 billion liters in 1975/76, targets were set for 3 billion liters in 1980 and 10.7 billion liters for 1985 (Goldemberg, unpublished).[19] Favorable financing was put in place by the government, including credit guarantees and loans to expand ethanol production at interest rates which in real

[18] The energy crisis of the 1970s also spurred additional oil exploration and production efforts, the launch of a nuclear program and the ProOleo Program (Interviews, 2010-2011).

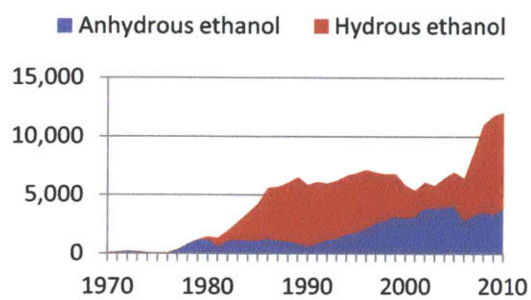
[19] By 1977, the target for 1980 of 3 billion liters was already met.

terms were below that of inflation (MIC, 1981; Barzelay, 1986; Walter et al, 2007). Additional measures included: setting ethanol prices for producers 5% higher than a comparable unit of sugar; supporting R&D in areas such as ethanol productivity with grants; setting fuel economy standards for ethanol-based engines; placing import restrictions on ethanol to protect the emerging industry; requiring that fuel stations include ethanol as a fuel option; state-owned energy company, Petrobras, made adaptations in distribution and refining; and the government incrementally increased blending requirements (Goldemberg, 2009; MIC, 1981; Lehtonen, 2007; Sandalow, 2006).

In terms of demand-side policies, measures included: Petrobras becoming a guaranteed buyer of specified amounts of ethanol each year; information campaigns promoting the link between ethanol use and national industrial strength; retail prices of ethanol being set below gasoline (59% of gasoline, with a guarantee not to exceed 65%); the state purchasing neat cars for a fleet of taxis for early demonstration; and favorable financing as well as vehicle registration fee rebates being made available for neat vehicle purchases (Barzelay, 1986; MIC, 1981; Moreira and Goldemberg, 1999; Goldemberg, 1994 and unpublished; BNDES and CGEE, 2008; OECD/IEA, 2010).

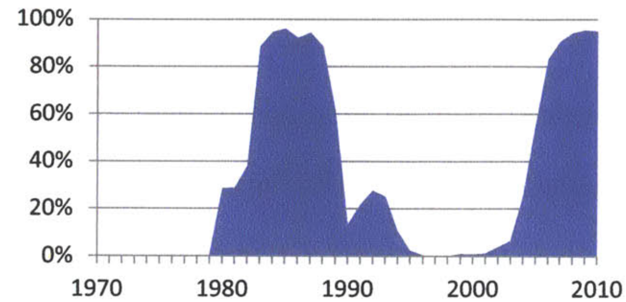
This bundle of supply-side and demand-side measures, reflecting a range of policy approaches from direct deployment to incentives succeeded in triggering growth of ethanol production and fleet adaptations in conjunction with a repurposing of existing infrastructure and markets (Figures C5 and C6).

Figure C5: Production of Ethanol in Brazil
(Thousand Tons of oil equivalent/TOE)



Source: MME data, 2011.

Figure C6: Share of Newly Registered Automobiles Designed for Ethanol Use in Brazil (Neat and Flex Fuel Vehicles)

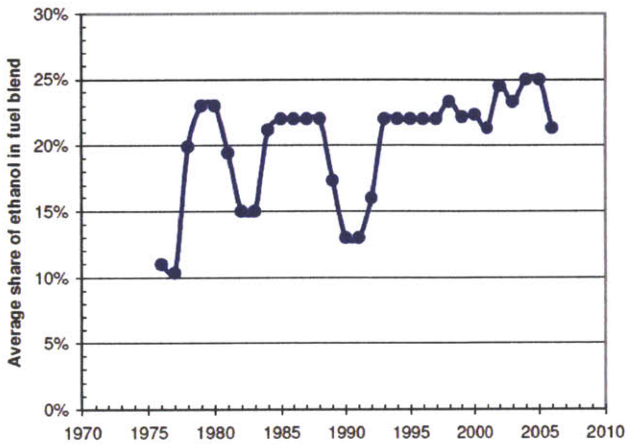


Source: Associacao Nacional dos Fabricantes des Veiculos Automotores /ANFAVEA data, 2011, Table 2.5. Note this does not account for vehicles converted from internal combustion to neat technology.

At the time, measures were put in place with little public debate, as Brazil was governed by military regime and, arguably, alternatives appeared to be limited.

In technology terms, ethanol adoption initially centered on blending anhydrous ethanol into gasoline that could be used in spark-ignited, internal combustion engines with no real vehicle adaptations for the years 1975-1979. By the end of the 1970s, blending had risen from roughly 10% to 20-25% (Figure C7).

Figure C7: Share of Anhydrous Ethanol in Gasoline-Ethanol Fuel Blends



Source: Walter and Dolzan, 2009, referencing F.O. Lichts, 2006.

With the second oil shock in the late 1970s, the ProAlcool Program shifted from utilizing untapped capacity and modifying existing sugar mills. The Program became more robust with objectives now focused on the production of vehicles that could run on E100, increased production of hydrous ethanol, and construction of autonomous distilleries to extend the once under-utilized capacity to meet new targets (Federal Decree 83700, 1979; MIC, 1981; Demetrius, 1990). A national distribution network was established to manage hydrated ethanol in all service stations with supply guaranteed by controls (USDA, 2011). An arrangement was also made with auto-manufacturers – VW, GM, Fiat, Mercedes Benz and Toyota - to produce a fleet of neat vehicles dedicated to hydrous ethanol. Favorable financing was provided to auto-manufacturers to adjust their production lines (Sandalow, 2006). Ernesto Stumpf's earlier research on engine utilization of E100 was advanced by the auto industry and auto rebuilders (MIC, 1981; Communications with ANFAVEA, 2012),[20] and as a result of the agreement between the Brazilian government and auto manufacturers, neat vehicles were commercially introduced in Brazil in 1979 with the Fiat 147 being the first (Revista Veja, 1979). These neat vehicles had modified engines with increased compression ratios and altered fuel injection, more corrosion-resistant materials, an auxiliary cold-start system and colder spark plugs to disperse heat (Joseph Jr., 2010). This change in the auto fleet produced an immediate demand shift to E100 (MIC, 1981).

In the 1980s, Brazilian biofuels adoption followed a steep growth curve, as the enabling environment underwent other change. The Brazilian economy experienced high inflation and foreign debt, due in part to the economic shocks of the 1970s (Rosillo-Calle and Cortez, 1998).During this time, the World Bank provided a $250 million loan to support the continued advance of the ProAlcool Program (World Bank, 1983; Demetrius, 1990; OECD/IEA, 2010b). In 1984-85, the national government transitioned from a military regime to the first civilian regime in 20 years. Amidst the political realignment, public investment and subsidies were reduced. By the mid-1980s, world oil prices had collapsed and world sugar prices had risen, leaving ethanol costs at an extreme and relative disadvantage versus gasoline or sugar.

[20] According to many accounts, Stumpf's vehicle experiments convinced President Geisel during a visit in June 1975 that an ethanol program was a viable option. This visit occurred before the launch of ProAlcool in November of the same year (Hammond, 1997; Joseph Jr., 2010; Interviews, 2010; Goldemberg, unpublished; BNDES and CGEE, 2009; Walter, 2009).

Taken as a whole, Stage 1 reflected substantial activity. Brazil's national government effectuated an aggressive early transition by essentially creating and guaranteeing a market as well as facilitating distribution. The government spurred change through price setting and soft financing. Automobile drivers responded by adopting neat or neat-converted vehicles. The automotive and sugar industries adapted their inner workings and scaled up relevant vehicle and fuel production. Ethanol output increased 3.4% per year on average (MME, 2011). Cars designed for ethanol rose from 0 to 88% of cars sold (ANFAVEA, 2011).[21] Ethanol as a share of transport fuel rose from 0.7% to 19% (MME, 2011) and, more specifically, its share of automotive fuels (namely ethanol and gasoline), rose from 1 to 51% (Ibid).

The science and technology of ethanol and automotive production benefitted from rapid learning with usage as well as more formal R&D. Automobile drivers and mechanics, ethanol mill owners, and farmers underwent accelerated learning which complemented more targeted research and development efforts on the part of auto manufacturers, the sugar industry, academia, and government programs (see Innovations and Adaptations).

Following the launch of ProAlcool, infrastructure was adapted with the addition of annex distilleries to existing sugar mills, plus adjustments to the fuel distribution network and ICE vehicles. These measures were later amplified in 1979 with more robust development, including the building of autonomous ethanol distilleries, production of a

[21] This does not include aftermarket conversions of vehicles to the neat features.

new fleet of neat vehicles, and conversion of fuel stations to sell E100. In sum, this stage reflected robust and disruptive change in the auto fleet, fueling infrastructure and fuel supply, peaking in 1986 with 96% of the newly registered cars designed to use E100.

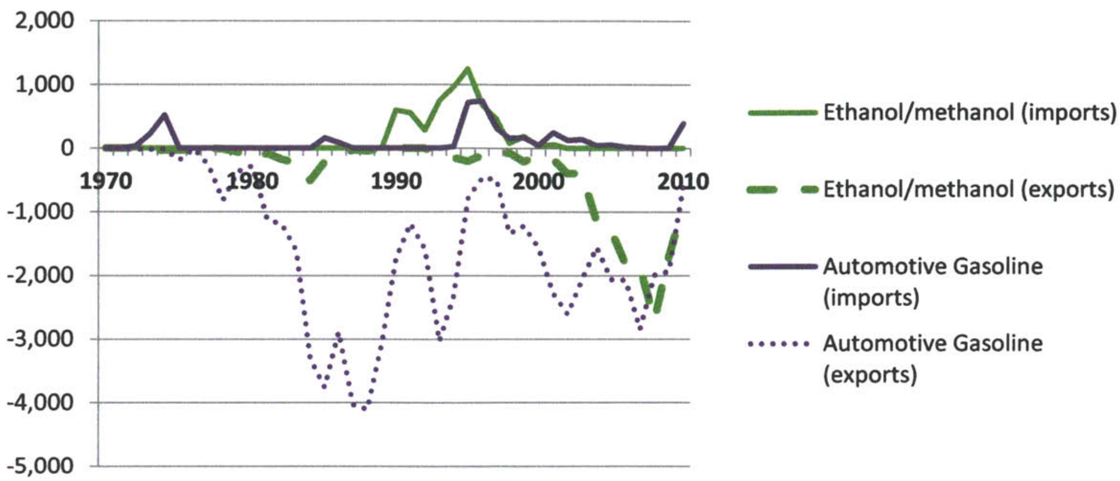
Stage 2: Retrenchment, Deregulation, and R&D *(1989-2002)*

In marked contrast to the mobilization of the last stage, the second stage of the Brazilian biofuels transition includes retrenchment on the part of the government and consumers. However, key progress continued in R&D and other industrial advance.

During this second period, the government focused on stabilizing the economy by implementing a series of reforms which included the removal of nearly all Stage 1 ProAlcool policies, except for the blending requirements (Federal Bill 8,723/1993, see also Timeline, Appendix). The auto vehicle fleet reverted back to standard ICE vehicles from neat vehicles specifically designed for E100 use.

Ethanol production dipped in the late 1980s and early 1990s (Figure C7) driven by a recovery in world sugar prices, low oil prices, and periods of weather which produced unfavorable conditions for ethanol production. At one point, the demand for ethanol exceeded the available supply, necessitating imports to meet the shortfall (Figure C8).

Figure C8: Exports and Imports of Ethanol/Methanol and Automotive Gasoline
(Thousand TOE)



Source: MME data, 2011.

The ethanol supply shortfall - together with early-staged technology issues, shifting political-economic conditions, lower gasoline prices, and new policy support for less costly non-E100 vehicles - combined to erode consumer confidence in the ethanol program (Interviews, 2010-2011). Car manufacturers responded by restructuring production lines back to conventional, gasoline-fueled cars (Sandalow, 2006). During much of the 1990s, retrenchment of the ethanol initiatives continued as economic and institutional shifts occurred (Library of Congress, undated). Broadly, policies were reoriented toward privatization, competition, globalization and decentralization of the energy sector (IEA, 2006; James A. Baker Institute for Public Policy of Rice University, 2004; EIA, 2012). Petrobras was partly privatized in 1997.[22]

[22] The Brazilian government retains ownership of 54% of Petrobras' common shares with voting rights. The Fundo Soberano and Banco Nacional de Desenvolvimento Economico e Social (BNDES), a federal-level public company linked to the Ministry of Development, Industry and Foreign Trade, each hold 5%, giving the government 64%

The electricity market was liberalized (GTZ, 2007), and the sugar-ethanol industry was deregulated (Akiyama et al, 2001). The sugar-ethanol industry evolved with professionalization of its management base, modernization of mills, and international companies as well as foreign capital entering into the ethanol production chain (Compean, 2009). As the above changes took hold, a tax mechanism was also put in place favoring cleaner fuels (Triana, 2011; Rosillo-Calle and Cortez, 1998).

From 1999 onwards, Brazilian ethanol was produced without government subsidies in the production or market chain (Dornelles, 2010). Professional associations, like the Sao Paolo Sugarcane Agroindustry Association (Uniao da Agroindustria Canavieira de Sao Paolo/UNICA) emerged and ethanol producers established the Brazilian Ethanol Exchange System (Bolsa Brasileira de Alcool/BBA), a voluntary contractual model for sugarcane pricing (BNDES and CGEE, 2008).

In terms of institutions, the IAA and Planalsucar were dismantled, and the decree which established ProAlcool was revoked (IEA, 2004). Copersucar, the Sao Paolo cooperative of sugar industry actors, continued many of the dismantled institutions' research activities.[23] Its R&D entity CTC partnered with the state of Sao Paolo's research foundation FAPESP to extend sugarcane research in genomics (Arruda, citing Arruda,

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control. The remaining 36% of the shares are traded on the Bolsa de Valores, Mercadorias and Futuros de Sao Paulo (BOVESPA) (Petrobras, 2012).

[23] Entering the 1980s, Planalsucar supposedly lost researchers to Copersucar and individual mills. In the period which followed, Copersucar conducted parallel lines of research in crop diversification, uses for vinasse and bagasse, and biological control (Sorj and Wilkinson, 1993).

2001). Efforts in this regard drew investment and the development of start-up companies that would lead to the establishment of Ag-biotechnology R&D centers around Campinas, Sao Paolo in recent years (Stage 3) (Aruda, 2011). A newly-formed university network for the development of the sugar-energy sector, Rede Interuniversitária para o Desenvolvimento do Setor Sucroenergético (RIDESA), and the Ministry of Agriculture absorbed members of IAA and Planasucar's institutional teams and infrastructure (Rosillo-Calle and Cortez, 1998; Interviews, 2011).[24]

As the institutional landscape shifted, two new entities were formed, including the National Energy Policy Council (Conselho Nacional de Politica Energetica/CNPE) and the National Petroleum Agency (Agencia Nacional do Petroleo/ANP), later renamed the National Agency for Petroleum, Natural Gas and Biofuels in 2005 (USDA, 2010). CNPE is an executive branch agency charged with the formulation of energy policy and directives, issuing key programmatic directives associated with biofuels (Lei nº 9478/1997; Decreto nº 3520/2000, Ibid). ANP implements national biofuels policy, overseeing regulation and quality standards (Ibid).

At the infrastructural level, decline was evident. Neat vehicles as a share of the new Brazilian car fleet declined from 61% to 4% (ANFAVEA, 2012) in conjunction with the share of total transport fuel derived from ethanol decreasing from 20% to 12% (50% to 33% for primary automotive fuels) (MME, 2011). As momentum for biofuels dissipated

[24] Ridesa carried the work of Planalsucar forward, absorbing the technology institutions and coordination of experimentation stations (Ridesa, 2012).

and the markets underwent a period of stagnation, the established sugar-ethanol industry infrastructure and fuel distribution network remained.

As the biofuels path receded with sweeping policy and institutional shifts, important progress, nonetheless, continued in science and technology. Experimentation and modernization by farmers, sugar-ethanol mills, industry labs and universities advanced the knowledge in ethanol production and management (see Innovations and Adaptations). Less visible at the time was the R&D progress in niches of the automobile sector. In particular, engineers working for Fiat subsidiary Magnetti Marelli and Bosch began adapting flex fuel technology from the United States to Brazilian market needs (Sandalow, 2006; see Innovation and Adaptation), setting the stage for a resurgence.

Stage 3: Resurgence (2003 - the Present)

The third stage of Brazil's biofuels transition is defined by the commercialization of new automotive technology by industry; continued agricultural development; modest government engagement in a more deregulated market; mobilization of the sugar industry as an electricity market player; and the reemergence of consumer demand for ethanol and ethanol-designed vehicles.

In what could be described as the technological basis for a 'comeback' in Brazilian biofuels, flex fuel technology was commercially launched in March of 2003 with VW's Gol 1.6 Total Flex. The Gol adapted earlier flex fuel technology with knowledge accrued in multiple decades of ethanol use and R&D efforts to produce advanced flex fuel functionality, suited for a broader automotive market. The key innovation involved use of an existing sensor in the vehicles, rather than a separately dedicated probe, enabling costs to remain essentially at par with conventional, gasoline-powered vehicles

(Interviews, 2011-2012; de Lima, 2006; see Innovations and Adaptations). In conjunction with this, tax credits for neat vehicles were extended to flex fuel vehicles, reducing costs for consumers and strengthening vehicle appeal for both consumers and producers (Ibid). The technology caught on with other major auto manufacturers releasing flex fuel models shortly thereafter, including Chevrolet, Fiat, Ford, Honda, Kia, Mitsubishi, Nissan, Peugeot, Renault, and Toyota (ANFAVEA, 2011; Interviews, 2010-2012). Flex fuel technology has since evolved in terms of fuel efficiency, compression ratios and engine power, and been applied to motorcycles and buses (Ibid).

Drawing upon earlier experience with the ProAlcool, ProOleo and OVEG programs, the Brazilian government established the Biodiesel Production and Use Program (PNPB) in 2004 to substitute diesel fuel with domestically produced biofuels from vegetable oils, like palm, soy and castor (N° 11.097; Noguiera, 2005). In conjunction with environmental and energy supply security aims, the program focused on fuel diversification, rural development and job creation to reduce regional income disparities.

In terms of basic programmatic rules, the PNPB set biodiesel voluntary blending requirements at B2 (2% biodiesel) which subsequently shifted to mandatory rules with stepped increases up to B5 in 2010 (Resolucao N° 6/2009; ANP, 2012; Interview, 2012). Standards testing has been overseen by the Ministry of Science and Technology (Ministerio de Ciencia e Tecnologia /MCT) with the participation of the national auto-manufacturers association (Associacao Nacional dos Fabricantes de Veiculos Automotores/ANFAVEA).

The PNPB utilizes a public auction system which sets a volume for production quantities and an average sales price (United States Department of Agriculture/USDA, 2011). These biodiesel auctions began in 2005. Through these, the Petroleum National Agency (Agencia Nacional do Petroleo/ANP) contracts for future production and biodiesel companies must hold a 'social fuel seal' (SFS), indicating they have contracts with family farmers, to participate. As of March 1, 2012, twenty-five auctions have occurred (ANP, 2012).

Other than blending requirements, standards and auctions, PNPB policies consist principally of tax incentives/exemptions (i.e. CIDE, PIS/PASEP and COFINS), a producer subsidy for small family farmers in the poorest states, and a preferred seal to encourage use of feedstock from small famers (USDA, 2011). If biodiesel fuel producers acquire such feedstock from small Brazilian farmers, they are eligible for federal tax reductions up to 68-100%. If feedstock purchases are made from other groups, the maximum reduction is 31%.

In 2010, biodiesel production reached 2.4 billion liters with production capacity equaling 5.8 billion liters per year from 67 authorized plants (Shaeffer et al, 2011). To date, biodiesel production has outpaced targets, but challenges have been encountered in terms of access to capital, seed optimization, weather and lack of support services in areas like the Northeast (Interviews, 2011-2012). Petrobras has entered this area of the liquid fuels market with three production plants in the Northeast and two R&D plants in

Rio Grande do Norte (Petrobras, 2012). Related to this, Petrobras is securing biodiesel feedstock with a stated goal of working with 80,000 families through long-term agreements, guaranteed prices, seed distribution and technical assistance in addition to an earlier program for soil correction (Ibid).

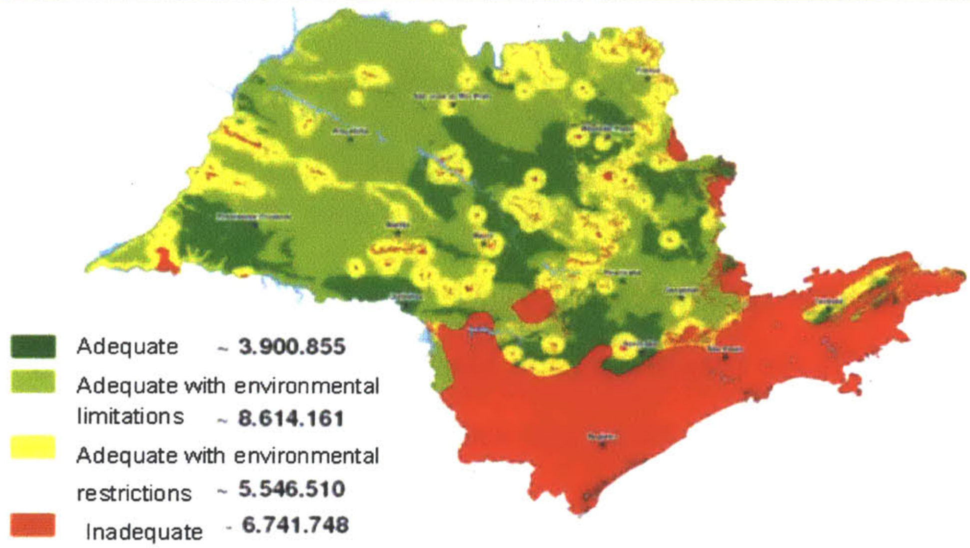
In addition to developments with flex fuel technology and biodiesel, new opportunities for sugar producers emerged with reform in the electricity sector. The wholesale, liberal market that was set up with privatization in the 1990s was replaced with a new model in 2004 which included power auctions (Lei No 10,848/2004 and Decree 5,081/2004; OECD, 2004; GTZ, 2007; EIA, 2012). These power auctions allow independent power producers, such as sugar mills, to participate in concession bidding for long-term power purchase agreements with energy distributors in a pool organized by the electricity regulatory authority (Agência Nacional de Energia Elétrica, ANEEL).[25] This reform was adopted to spur competition while addressing market failures. Consequently, it opened a new line of business for sugar mills to compete with power generation from sugarcane waste. Up to that point, bagasse had been used by sugar mills to produce electricity for self-sufficiency. In 2007, an auction was held specifically for renewable power producers supplying power from biomass, small scale hydro, and wind power (GTZ, 2007).

[25] Regulation 2003 (1996) established the right for independent power producers and self generators to operate. By paying transmission charges, they have 'free access' to the interconnected grid and to distribution lines (GTZ, 2007).

In recent years, Brazil has also taken a lead in international training and diplomacy related to biofuels, particularly with industrializing countries (Interview, 2010; Meyer, 2010). As of early 2010, Brazil had signed over 60 agreements on bilateral technical cooperation with countries from Central America, the Caribbean, Africa and the United States (Brianezi, 2010; Interviews, 2010). Brazil also put forward the idea of an International Biofuels Forum which was officially launched in the United Nations in 2007 (United Nations, 2007; Whitehouse, 2007). The Forum and other international efforts by Brazil are actively promoting the creation of an international commodities market for biofuels, related jobs creation, and more uniform standards (Ibid; Interviews, 2010).

In 2009, the Ministry of Agriculture, Livestock and Supply (MAPA) outlined agri-ecological zoning, which delineated protected land and other areas that are not suitable for large-scale sugarcane farming (Interviews, 2010; USDA, 2010; Figure C9).

Figure C9: Agroecological Zoning – State of Sao Paolo



Source: Guardabassi and Goldemberg, 2011.

Based on a strategic environmental assessment, this zoning delineates regions of ranching and agricultural land where sugarcane is not currently grown to inform infrastructure investment decisions, financing policies, tax regime changes and potential socio-economic certification (CGEE and BNDES, 2008, citing Strapasson, 2008). Soil, climate and other relevant scientific data is combined with information on land use, environmental legislation, etc to classify prime areas for sugarcane planning (Ibid; IEA, 2011).

The Federal government and State of Sao Paulo also passed laws to phase out the use of sugarcane burning in manual harvest, spurring mechanization (Macedo, 2005). Based on Federal Decree 2,661/1998, the practice of cane burning will no longer be possible in areas with a slope less than 12% within a set timeline, where mechanized harvest is possible. The State of Sao Paolo implemented a more aggressive plan which was then superceded in 2007 by an agreement between UNICA and the Sao Paolo state secretaries of the Environment and Agriculture and Supply for a more accelerated schedule (USDA, 2010).

As for other vehicular technology developments, Honda launched the first commercial, flex fuel motorcycle, the CG 150 Titan Mix in 2009, followed by an on-off road version later that same year (Abraciclo, 2009; Motodriver, 2009). By 2011, four flex fuel motorcycle models were commercially available and production equaled nearly 1 million units, increasing the existing market share to 57% (ANFAVEA, 2011; UNICA, 2011; Abraciclo, 2011).

Building on several years of testing and refinements,[26] the city of Sao Paolo in partnership with Cosan, UNICA and Viacao Metrolpolitiana and introduced a fleet of ethanol-powered buses in 2011 (Franca, 2011; Saker, 2009; Estado de Sao Paolo, 2008). Raisen, a joint venture involving Cosan and Royal Dutch Shell, supplies the bus fuel at 70% of the market price for standard diesel (Franca, 2011; UNICA, 2011).

Research and development continues at a number of Brazilian labs, schools and companies to advance the next generation of sugarcane and biofuels. The recently established national laboratory for bioethanol (Laboratório Nacional de Ciência e Tecnologia do Bioetanol/CTBE), Alellyx-Canavialis (Monsanto), Dedini, CTC-BASF,

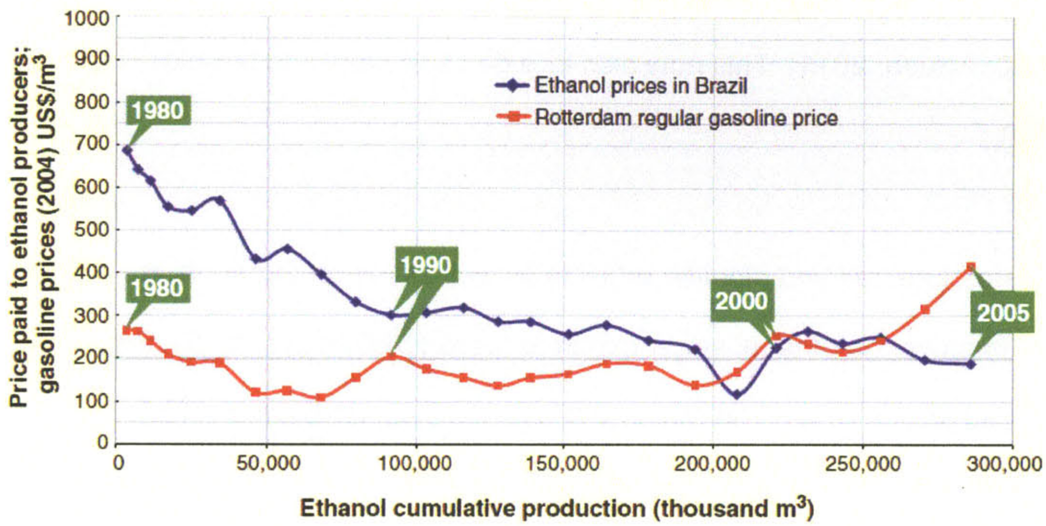
[26] The fuel injection timing and fuel nozzle size were modified, together with the compression ratio from 18:1 to 28:1 (Greencar Congress, 2007).

Petrobras-Novozymes, UNICAMP, Amyris, Butamax (BP-DuPont), Syngenta, Shell-Cosan, and IPT are among the regional research centers working in this field (Eisentraut, 2010; Arruda, 2011). This now also includes spillovers into bio-plastics (Interview, 2012).

Specific to infrastructure, rail and pipeline projects as well as export terminals are under development to improve the ethanol-sugar export facilities (OECD/IEA, 2010). Gasohol is sold at every fuel station (Ibid). The majority of stations also sell biodiesel (B5) and diesel, with some selling natural gas (Ibid, citing ANP, 2009).

Importantly, Brazilian ethanol became fully competitive with gasoline in the past decade (Figure C10) as production continued to rise. Consumer demand for flex fuel vehicles has also continued to grow (ANFAVEA, 2011 and 2012).

Figure C10: Ethanol vs. Rotterdam Gasoline Prices



Source: Goldemberg, 2007.

Naturally, scale-up and adaptation are not assured to be smooth processes. A combination of climate conditions, high sugar prices, and under-investment converged in 2010 and 2011, so that Brazil needed to import ethanol in order to meet its domestic demand (Platts, 2012). The Brazilian government has now adopted measures to limit ethanol supply shortfalls and increase sectoral investment (EIA, 2012). The government lowered the blending requirement from 25 to 20% and announced plans for Petrobras to expand its activities in the ethanol market (Ibid). In February of 2012, the federal government also announced a strategic plan which included $38 billion (65 billion reais) in new credit and financing support for biofuels at market rates (Lane, 2012; Reuters, 2012). Funds are designated for mills and independent sugarcane growers to expand yields and build up stockpiles (Reuters, 2012).

At the start of Stage 3, specially-designed ethanol vehicles represented 6% of new car sales (ANFAVEA, 2011). In 2010, they had risen to more than 95% (Ibid). Ethanol as a share of auto fuels also grew from 31% to roughly 41% (12% to 17% transport fuel) (MME, 2011). In 2008-2010, ethanol consumption exceeded that of gasoline (Ibid; (MME, 2011). Currently, about eleven auto manufacturers produce over seventy flex fuel models in the Brazilian market at a price that is equivalent to conventional car models, bringing choice and better economics to the consumer.

D. INNOVATIONS and ADAPTATIONS

Innovations and adaptations, based on analysis of the interview feedback, literature, and data, identified the following as prominent in the Brazilian biofuels trajectory:

- **Ethanol production** – Improved crop yields tied to enhanced seed varieties, changes in planting, harvesting, and fertilization practices; improved processing and logistical management and efficiencies;

- **Automotive technology** – Neat and Flex Fuel vehicle design;

- **Bioelectricity** – Use of high pressure boilers and grid connections to enable fuller utilization of bagasse waste as energy feedstock;

- **Biodiesel development** – New processing for bio-diesel;

Ethanol production

For the purposes here, technology development in ethanol production encompasses the planting and harvesting of sugarcane, extraction of sugar, and alcohol fermentation process. Based on an evaluation of this area, key advances were identified in increasingly resilient seed varieties; mechanization in harvesting; fertilizer adaptations, like vinasse; and logistical improvements in the timing, transport, storage and processing of sugarcane-ethanol.

Seeds

Specific to seed varieties, gains have been made through sugarcane research and breeding programs. With hybridization (i.e. crossing of seed varieties), breeding has modified the sucrose and fiber content; the amount of stalks; early maturity; resistance to pests, disease and flowering; regional particularities; plus adaptability and stability of variety, among possible traits (Guimaraes et al, 2010; Creste et al, 2010; Gazaffi et al, 2010, citing Matsouka et al 1999a, 1999b).[27] Roughly six new commercial varieties per year have been obtained, furnishing more than 600 seed varieties in Brazil (CGEE and BNDES, 2008; Interviews, 2010-2012).

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[27] For context, estimates indicate that the selection and launch of a new seed variety requires no less than ten years and includes the testing of experimental clones, the evaluation of yield variation in different cultivation environments, and the monitoring of disease and pest outcomes (Dal-Bianco et al, 2012; CGEE and BNDES, 2008, citing Ridesa, 2008). On average, one new commercial seed variety may emerge from every 250,000 seedlings that are assessed in a breeding program's early testing and development stage (Cheavegatti-Gianotto et al, 2011).

In terms of key contributors, Ridesa, the CTC, the Instituto Agronomico de Campinas (IAC) and CanaVialis are among the major players in sugarcane seed development (Creste et al, 2010; Souza and Sluys, 2010; Cheavegatti-Gianotto et al, 2011). Ridesa, the inter-university network that absorbed activity and infrastructure of Planalsucar in the early 1990s, is now a public-private partnership (PPP) consisting of 300 companies and nine federal universities engaged in the development of the sugar and alcohol sector (Ridesa, 2012; Souza and Sluys, 2010). It holds the largest public collection of sugarcane genotypes in Brazil (Ibid). Former Copersucar R&D entity CTC manages what is likely to be one of the most important private germplasm collections in the world with restricted access (Creste et al, 2010; Souza and Sluys, 2010). This is an outgrowth of partnering by the CTC with the State of Sao Paolo research foundation (FAPESP) to extend sugarcane research in genomics (Arruda, 2011, citing Arruda, 2001). The IAC is the oldest R&D institute in Latin America dedicated to optimization of agriculture and applied fields. It holds a key academic-based seed collection. Monsanto subsidiary, CanaVialis is also engaged in seed varietal management and genetic improvement in Brazil. Like the CTC, it has a developing collection with restricted access (Creste et al, 2010; CanaVialis, 2012). Overall, work currently by Ridesa and the CTC represents 95% of the seed varieties used in Brazil (Souza and Sluys, 2010).

Mechanization

The mechanization of processes also mattered in Brazilian biofuels adoption. Principal mechanization of sugarcane between 1975 and 2005 involved the standardization of operations, the incorporation of new planting equipment, operational training, etc (Ibid).

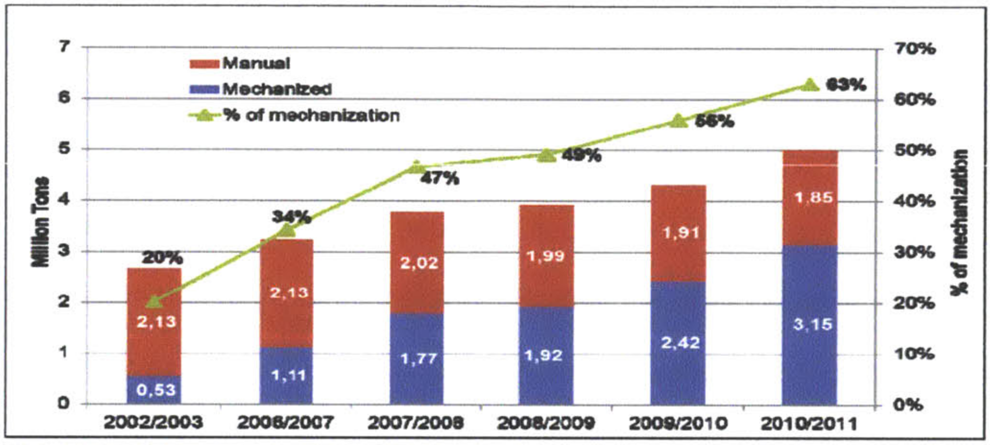
This drew upon technological development that occurred in Australia, Cuba and the US to optimize the recovery of plant stalks plus the economic elimination of straw in harvest practices (Magalhaes and Braunbeck, 2010b).[28] Mechanization led to reduction in production costs which are currently the lowest worldwide (Ibid). Actors driving this change included sugar mill technicians, regional manufacturers, and research institutes interested in cost reductions (Ibid; Braunbeck and Magalhaes, 2010). Among principals mentioned in the research, agro-energy-infrastructure company, Dedini, which produces agricultural equipment as well as turn-key plants, was regularly cited as a key private sector player in the modernization and mechanization of sugar-ethanol production during this period (Interviews, 2010-2012).

When combined with practices, like fertilization, mechanization is deemed to be a crucial explanation for why limited soil degradation occurred in Brazil after decades of sugarcane plantings on the same soil (Rosetto et al, 2010). Importantly, mechanization has been spurred in recent years for environmental and economic reasons. In environmental terms, awareness has increasingly acknowledged the detrimental effects of emissions and soot from combustion associated with manual harvests. The Brazilian government has instituted measures to eliminate manual harvesting practices by 2020 (Jank, 2009; Goldemberg, 2010). In terms of economics, mechanization reduces manual jobs and increases plant residue that may be burned for bioelectricity. Figure D1 shows the evolution of mechanized harvesting in the State of Sao Paolo between

[28] The principles underpinning this are known as (1) the Soldier or Louisiana system which harvests the whole stalks and lays them parallel to each other, and (2) the Push-Rake system which cuts and loads whole stalks in a disorderly manner (Magalhaes and Braunbeck, 2010b).

harvest seasons 2002/3 and 2010/11 with an increase in mechanization from 20 to 63%.

Figure D1: Evolution of Mechanical Harvesting in the State of Sao Paolo



Source: Guarabassi and Goldemberg, 2011.

As a consequence of the ongoing transition in Brazil from manual harvesting to mechanization, as well as environmental interest to reduce carbon releases in farming, research i at the CTBE national lab s focusing on conservation tillage methods which include no tillage (i.e. soil preparation without mechanical agitation) and limited cultivation of the soil (Malgalhaes and Braunbeck, 2010). According to one agro-scientist, agriculture machinery manufacturers contributed to mechanization, but are not receptive to new trends related to low/no tillage (Interview, 2010).

Fertilization - Vinasse

For decades, nutrient enhancement of soil through fertilization is an area that has been studied by Brazilian sugar producers, industry associations (Copersucar/CTC) and government agencies (IAA). An example of Brazilian innovation in fertilizers entailed the science and practice of fertilizing with vinasse.

Vinasse is a liquid by-product of ethanol and cachaca production that is a rich source of potassium, sulfur and other nutrients (Ibid; Mutton et al, 2010). Its high acidic quality also means that it can act as an environmental toxin if used inappropriately (Ibid; Interviews, 2010). Environmental reports from the 1970s indicate that the sugar and alcohol industry contributed to environmental pollution, due to the dumping of vinasse (Mutton, 2010). Large quantities of this substance degrade the quality of raw outputs and can cause an area to become fallow (i.e. useless for agriculture), due primarily to high salinization and ion lixiviation of the soil (Mutton et al, 2010, citing Ferrerira, 1980). Early research by Professor Nadir da Gloria of Usina da Pedra was extended by the sugar industry and academic/government researchers to identify not only a proper dosage for sugarcane nutrition, but process enhancements which included spraying from trucks and automated feeding (Ibid; Ibid, citing Carvalho, 2007; Braunbeck and Neto, 2010). Advances in understanding vinasse nutrient-toxin levels led to altered fertilization practices which: enhanced sugarcane yields; optimized waste management; reduced environmental impacts; and, if done with ferti-irrigation, reduced costs on fertilizer imports (Mutton et al, 2010; Interviews, 2010-2012). While other opportunities for use exist, vinasse is used today principally for fertilizing grounds in the proximity of ethanol-producing mills in Brazil (Cheavegatti-Gianotto et al, 2011). While gains are clear, vinasse remains a subject of study.

Logistics and Information Management

Areas such as logistical planning as well as operation and information management have also played an important role in improved ethanol production in Brazil. The global advent of electronic monitoring and navigation devices, together with digital communications, and advanced management practices have enabled efficiencies to be incorporated across the Brazilian agro-industrial-ethanol chain.

One specific area related to planning entails the synchronized logistics of harvesting, loading and transport systems which are responsible for the milling rate of sugar mills (Braunbeck and Neto, 2010). A guiding principle is to keep the mill in constant operation with little idle time or excess stock, as cane can spoil quickly (Ibid, citing Chiarinelli, 2008; Interviews, 2010-2012). Consulting related to agricultural management and integrated information technology (IT) solutions opened with the deregulation of the industry and mill optimization of the 1990s (Arraes et al, 2010). In particular, enterprise resource planning -- management software which utilizes process management and IT for logistics, finance, purchase and storage management has advanced in the Brazilian agro-industry with companies, like TOTVS, SAP and Oracle (Ibid).

More recently, Precision Agriculture is a new direction of development, which leverages global positioning systems in equipment, and productivity mapping (Inamasu and Neto, 2010). To date, Precision Agriculture has been used primarily for soil correction. If adopted more widely, it may serve as a guide for crop management by identifying areas of low productivity and by improving knowledge with quality-related parameters.

Select Gains with Sugarcane

In conjunction with the above innovations and adaptations, Brazilian sugarcane productivity grew by 66% between 1975 and 2010 in terms of the tonnage of sugarcane produced per hectare, with an increase of 34% in the sugar yield per tonnage of hectare for the same period (Dal-Bianco et al, 2012, citing CONAB, 2011 and MAPA, 2009). Figures D2 and D3 illustrate aspects of this.

Figure D2: Sugarcane Production
(Tons)

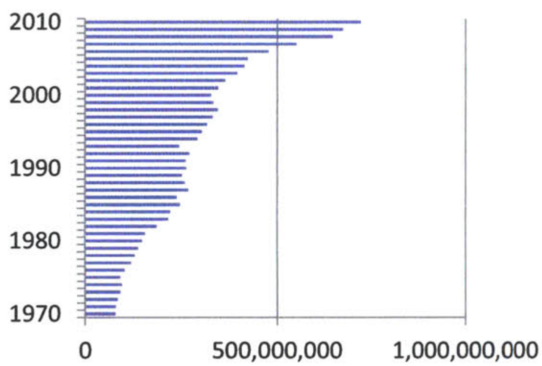
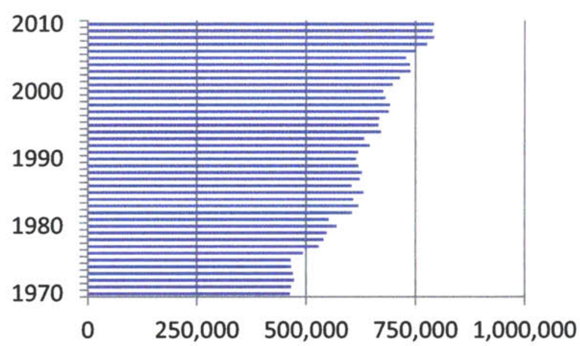


Figure D3: Sugarcane Yield
(Hg per Hectare)



Source: FAOSTAT data, 2012 for both figures.

These gains enabled Brazil to be the world's largest sugarcane producer with roughly 7.5 million cultivated hectares producing about 612 million tons of sugarcane in the 2009-2010 harvest season (Cheavegatti-Gianotto, 2011). In 209, roughly half was used to produce sugar with much of the rest used in the production of about 25 billion liters of ethanol (Ibid, citing CONAB, 2009). Combined exports of sugar and ethanol in 2009 generated almost $10 billion in revenue, making sugarcane products the third largest export for Brazil (Ibid).

Automotive

In terms of automotive technology and biofuels, two signature developments occurred in Brazil during the period studied -- the commercialization of the neat vehicle in 1979 and flex fuel vehicle in 2003.

Neat Vehicle Technology

Historically, ethanol and vehicle technology had been tested extensively at labs like the CTA in the period leading up to the launch of ProAlcool. Building on this work, the auto industry signed an agreement with the government for rapid production of the neat vehicles in 1979. Auto-manufacturers refined and commercialized the neat technology with financing for investment provided by the Brazilian Development Bank (Banco Nacional de Desenvolvimento Economico e Social/BNDES) (Interview, 2012). Specific to vehicle changes, adaptations were made for increased compression ratios, use of duel carburetors, automatic cold starting, use of nickel coating and more corrosion-resistant liners, among others (Bastin et al, 20120, citing Figuerido, 2006). Initially commercialized neat models were released in 1979 and appeared in government fleets, such as that of TELESP in Sao Paolo (Gatti, 2010; Joseph Jr, 2010). Neat vehicles diffused via taxis and then mainstream use.

Flex Fuel

The breakthrough in flex fuel technology which optimized a Bosch patented-design (Bastin et al, 2010) revolutionized contemporary Brazilian biofuels development. Brazilian flex fuel advances emerged with Magneti Marelli, a subsidiary of Fiat based and competitor of Bosch, moving beyond the costly oxygen probe (fuel-line capacitive sensor) of an earlier design to utilize an existing sensor (oxygen lambda) found in the exhaust area of vehicles, allowing the gasoline-alcohol ratio to be determined (Interviews, 2012; de Lima, 2006). Bosch engineers employed the re-adapted sensor with electronic injection software in prototypes for GM, VW and Fiat (Ibid; Bastin et al, 2010). Magneti Marelli extended the design with an algorithm that calculated the fuel composition, increasing the accuracy of the system without raising the cost (Ibid). The optimized technology allowed cost reductions from the unification of several differentiated parts, namely ignition wire harnesses, injection valves and fuel pumps (Bastin et al, 2010, citing Abreu and Ribeiro, 2006). The release of flex fuel technology in 2003 revolutionized the auto fleet, enabling consumers to apply a simple rule of thumb at the pump which held that ethanol would be a better buy if its price were 70% or less than that of gasoline. This difference accounts for the variance in heat value and octane index (Costa and Sodre, 2010).

Bioelectricity

Adaptations with co-generation technology in the sugar-alcohol mills allowed biofuel residuals (i.e. bagasse, a form of biomass) to be used as a feedstock for electricity (Arruda, 2011). This enhanced mill self-sufficiency, eventually enabling mills to sell surplus electricity to the grid (Ibid). Higher pressure boilers were needed for mills to do this (BNDES and CGEE, 2008; Ibid, citing Horta Noguiera, 2006). Regulatory reform, namely the introduction of RET-based power auctions in 2007, and other technology improvements also allowed this development to go forward. In 2008, the first biomass-only reserve auction was held by the government for 2,379 MW of power derived from sugarcane and napier grass (IEA, 2011).[29] In that year, 4% of electricity was derived from biomass (Arruda, 2011, citing Jank, 2008).

Bio-diesel

While biodiesel has been researched at various points in time in Brazil, recent progress offers some promise. An example of such progress is in the development of a type of bio-diesel product, called H-bio. Petrobras' R&D center, Centro de Pesquisas Leopoldo Americo Miguez de Mello (CENPES) has developed H-bio through a process of hydrogenation, specifically catalytic hydrogenation and cracking of vegetable oils, rather than a common method of trans-esterification (Green Car Congress, 2006). This allows vegetable oil from various source feedstocks to be mixed into a mineral oil directly in a refinery unit (Ibid; Petrobras, 2009). This new approach is designed to eliminate waste; increase fuel quality; and complement growing bio-electricity practices (Green Car Congress, 2006). It aligns with existing requirements for diesel handling; optimizes diesel fuel processed at the refinery; allows flexibility in load processing; and may reduce testing since the product mimics existing diesel products in use (Ibid). As of 2008, four of twelve refineries owned by Petrobras were primed to produce this.

Sectoral Contributions

The strength of sectoral contributions in the above innovations and adaptations is laid out in Table D1 with some subjective weighting. This estimated weighting is derived

[29] As of 2009-2010, biomass power is to be supplied through 15 year power purchase contracts at an average final price of BRL 58.84/MWh (IEA, 2011; Interview, 2010).

from an evaluation of interview feedback, historical reporting, and case analysis. Weighting is indicated by the number of squares per category. It does not gauge the amount of indications mentioning a contribution, but rather a perceived strength of a given contribution. Arguably, a contribution can be extensive in its pivotal impact, but small in relative cost or other terms. This section serves simply as a conceptual estimate of key actions that will be similarly replicated in other case chapters.

Table D1: Sectoral Contributions to Innovation/Adaptations

Innovation/Adaptation	National Government	Industry	Civil Society	Other (Academia, NGOs, etc)
Ethanol Production				
• Seed variety improvements	■■■	■■■		■■■
• Mechanization	■	■■■		■■
• Fertilizer – Vinasse	■■	■■■	■	■■■
• Logistics and Information Mgmt		■■		■■
Automotive Technology				
• Neat vehicles	■■	■■■	■	■■
• Flex fuel	■	■■■	■	
Bioelectricity				
• Boilers	■	■		N/A
• Grid interconnection	■■	■■		N/A
Bio-diesel	■■■	■■■		■■
• H-bio	■■■	■■■		

Note: 'Grid inter-connection' is listed with contributions from the Government and Industry, as Eletrobras is a major electric utility which is partly owned by the federal government and the rest is traded on BM&F Bovespa, New York Stock Exchange and Madrid Stock Exchange (Eletrobras, 2011). Biodiesel development has been done by *partly state-owned enterprise Petrobras and labs that are often jointly owned by the state, industry and/or academia. The listing reflects this accordingly. Bioelectricity contributions of groups in the Other category were not able to be determined with collected information*

From this table, trends and differences in sectoral contributions can be loosely seen. For instance, industry has been heavily involved in the four major areas of innovations and adaptations. The national government has played a role in nearly all. Other groups, such as academic institutes and labs, rank next for their inputs with civil society having the most limited role. In terms of cross-sectoral engagement, the automotive advances involve the most wide-ranging contributions, whereas the biodiesel and bioelectricity advances are the areas of innovation involving the least multi-sectoral involvement.

E. KEY DRIVERS and BARRIERS

The following highlights key drivers and barriers which emerged in interviews, case analysis and historical record review.

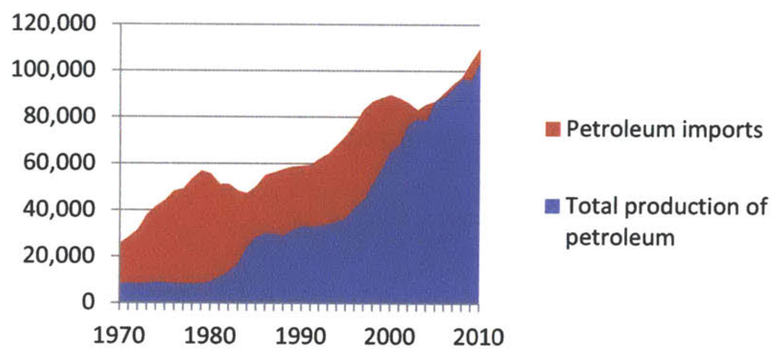
Drivers

- Reduction of oil imports/Improvement of the balance of payments/foreign exchange saving/National energy self-sufficiency/security
- Utilization of the domestic sugar industry
- Regional development
- The environment
- Favorable pricing

Reduction of Oil Import Dependence - Improvement of the Balance of Payments-Foreign Exchange Savings - National Energy Security/Self-sufficiency

The most consistently raised drivers of the Brazilian biofuels scale-up in the early period were the need to reduce oil import dependence and improve the balance of payments or savings on foreign exchange in the context of self-sufficiency. ProAlcool was launched with the stated aim to substitute imported oil with domestically produced ethanol, improving the foreign exchange position among other objectives. Brazil's heavy dependence on oil imports in the 1970s is evident in Figure E1.

Figure E1: Petroleum Imports and Production (Thousand TOE)



Source: MME data, 2011.

Tied to Brazil's early oil dependence were the extraordinary challenges associated with petroleum import costs increasing by a factor of 41 between 1970 and 1981 (Figure E2). Viewed from a slightly different angle, the share of Brazil's total import costs derived from oil rose from roughly 10% to 50% between 1970 and the early 1980s (Figure E3).

Figure E2: Import Costs of Petroleum for Brazil (Billion, nominal $)

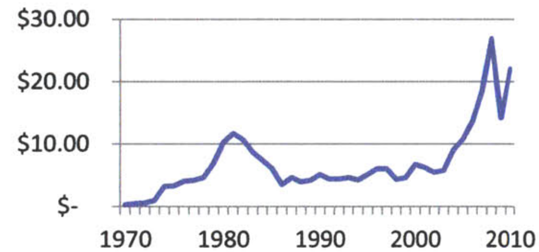
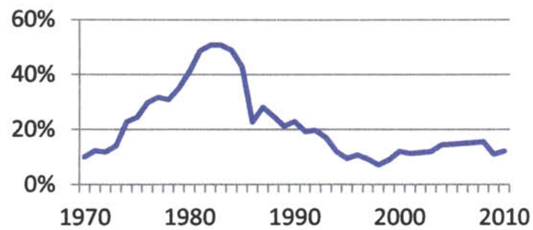


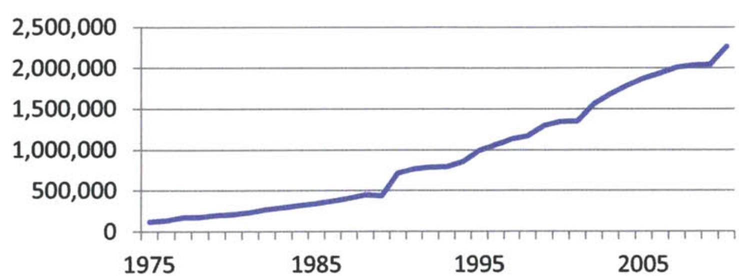
Figure E3: Petroleum as a Share of Total Import costs



Source: UN Comtrade data, SITC Rev 1, Petroleum/Petroleum products, 2011, for both charts.

Oil import dependence can be considered from a different standpoint in terms of knowledge of petroleum reserve. Figure E4 shows that knowledge and development of proven oil reserves in the 1970s was limited. Over the course of the period studied, domestic oil production increased substantially and Brazil became self-sufficient in oil on a net basis (MME, 2011). This strengthening of Brazil's oil independence altered the transport fuel playing field, making the later-staged innovation in flex fuel vehicles and growth of ethanol use more unusual, as it wasn't necessary in energy terms.

Figure E4: Proven Oil Reserves (1000 m^3)

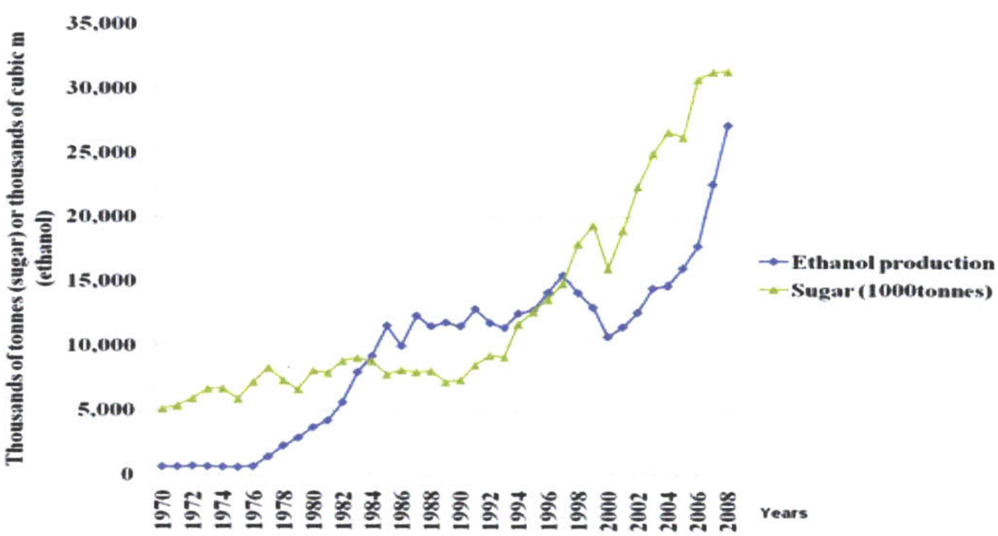


Source: Empresa de Pesquisa Energetica/EPE data, 2011, citing Agencia Nacional de Petroleo, Gas Natural e Biocombustíveis (ANP).

Better Utilization of the Indigenous Sugar Industry

Another regularly-stated driver of Brazilian biofuels adoption was the desire to better utilize spare capacity of the domestic sugar industry (Interviews, 2010-2011; Demetrius, 1990; Goldemberg, unpublished). This rationale broadly coincides with reported data on global sugar price flux and domestic sugar industry production (Figure E5) as well as information on major investment which preceded the oil shocks (Goldemberg, unpublished; Barzelay, 1986).

Figure E5: Brazilian Sugar and Ethanol Production, 1970-2008



Source: Goldemberg, 2011.

Regional Development – Jobs – Rural Development

The socio-economic aspects of biofuels – namely, jobs and regional development, particularly in rural areas -- were also indicated as key drivers of Brazilian biofuels development. Such priorities were noted in the ProAlcool decree, but have been criticized for not being met as well as other objectives (Demetrius, 1990; Barzelay 1986). According to some interviews, the rationale behind this particular driver in the 1970s was to reduce income disparities and urban migration (Interviews, 2010). In more recent years, jobs and economic development in rural areas were again mentioned as a high priority behind the launch of the new Biodiesel Program (Rodrigues and Accarini, 2009; de Almeida et al, 2007).

Environment

The environment was another key driver of biofuels substitution with the caveat that the significance of the environment increased over time (Interviews, 2010-2011). In the 1980s, environmental concerns in Brazil centered on urban air quality (Ibid), which ethanol use has improved (Macedo 2005/2007; Goldemberg and Lucon, 2010; CGEE and BNDES, 2008; Almeida et al 2007). For example, the decline in lead ambient concentrations in the Sao Paulo metropolitan region from 1.4 $\mu g/m^3$ in 1978 to < 0.3 $\mu g/m^3$ in 1991 is attributed to the ethanol blend (Goldemberg et al, 2008; Coelho and Goldemberg, 2004). In the 1990s, awareness grew with respect to sustainability and climate change, opening other bases of legitimacy for the biofuels endeavor (Interviews, 2010-2011). These concerns now manifest in interests related to certification standards of sustainable practices and environmental zoning (Ibid).

Pricing and Substitutes

Pricing is the only determinant of biofuels scale-up that was explicitly mentioned as <u>both</u> a driver and barrier. Pricing is a driver of biofuels usage today, for instance, when ethanol costs less than 70% of gasoline (its substitute) at the pump. Yet pricing is also a barrier to biofuels scaling, when sugar production is chosen over ethanol in mill production decisions because of favorable world sugar prices; or when standard internal combustion vehicles were purchased vs. neat vehicles, based on cost.

One way in which pricing is also a barrier, according to a substantial number of interviewees, lies with competitor prices for gasoline that have been maintained at artificially low and stable numbers, relative to international prices to counteract inflation (Interviewees, 2011-2012). Since 2002, fuel prices have not been directly set by the government (Calvalcanti et al, 2012, citing Decree 10.453/2002), yet Petrobras maintains a dominant position in the domestic fuels market and is working in a price-setter capacity. When Petrobras sets post-refinery prices, it currently is absorbing much of the international price variation (Ibid, citing Petrobras, 2002). This is done in Petrobras' capacity as an agent of the state, distorting the competitive landscape for liquid fuels (Interviewees, 2011-2012).

A related barrier is found in current taxes. Marcus Jank, the President of Brazilian Sugarcane Industry Association (UNICA), reported in 2011 that taxes for gasoline currently were 35% and for ethanol are 31%, producing a 4 percentage point difference between the two fuels (UNICA, 2011). This differential blurs the 70% rule of thumb used by consumers to identify comparative price advantages (UNICA, 2011).[30]

[30] In 2002, gasoline was taxed at a rate of 47% at the pump, declining now to 35% (UNICA, 2011).

Barriers

- Pricing and substitutes
- Technology performance and competitiveness
- Uncertainty

Pricing and Substitutes *(see under Drivers)*

Technology performance and competitiveness

The performance of biofuels and neat vehicles were regularly mentioned as a barrier in biofuels scale-up of the Stage 1. In short, early versions of both technologies were put into circulation in a learning-by-doing mode, so they were not yet refined. Over time, standards were put in place and auto manufacturers introduced modifications for technology issues, like material corrosion and cold starts (Joseph Jr, 2010; Interviews, 2010-2011).

Uncertainty

Another barrier was uncertainty. In early Stage 1, numerous accounts described a lag on the part of finance institutions to implement (Barzelay, 1986). Car manufacturers also did not robustly engage in ProAlcool activities until around 1979 (Ibid; Demetrius, 1990), possibly 'holding back' to gauge whether the overall program would gain full traction. The second oil shock appears to have solidified whatever uncertainty there may have been about reverting back to oil imports. In Stage 2, uncertainty also appeared to be particularly strong as the policy architecture for biofuels was dismantled.

F. CLASSIFYING CHANGE

To explain the type of energy system change which occurred, a number of dimensions are considered.

In terms of the source and direction of the Brazilian biofuels transition, the early stage was top-down. Even if some non-governmental actors, like the sugar industry, lobbied for a stimulus plan, the government set it in motion, leading to a reconfiguration in both the sugar and auto industries. In Stage 2, little occurred overtly to advance the energy transition. However, R&D continued behind-the-scenes with auto manufacturers, the sugar industry and academic labs. Stage 3 began with bottom up development in the auto and sugar sectors and more modest role played by the government, relative to Stage 1. Consumer demand and learning also fostered some bottom-up momentum of the period. Overall, this suggests a hybrid model which began as top-down and shifted to more bottom-up/mixed form.

Governmental intervention played out in different ways across the stages. In the first stage of conversion, change was directly deployed with the creation of a guaranteed market and distributional realignment. Regulated inducement was used in price setting. Incentives were also employed with soft financing for industry and car owners. In the second stage, government intervention was almost entirely removed except for blending requirements. In the third stage, a more market-based version of stage one instruments was used with the more limited and new biodiesel initiative. Direct deployment, regulated inducement and incentivizing were accomplished through a package of auctions and blending mandates. Specific to ethanol, blending rules were maintained. The tax credit for neat vehicles was extended to flex fuel vehicles. In addition, information and capacity-building approaches were used in agro-zoning and international cooperation.

When considering the displacement of traditional fuels with biofuels, the 3 stages are fairly distinct, as shown in Figure C4. Stage 1 was quite robust, rising from a negligible number to over 50% of automotive fuels. Stage 2 was essentially a reversal of some of the earlier progress. Stage 3 was a mixed scenario with a period of robust progress, which ultimately raised the share of biofuels from the low 30% range to the low 40% range of automotive fuels.

In terms of technology change, the biofuels, automotive, and bioelectricity technologies each have their own character.

- For biofuels, radical and incremental technology change was evident in agricultural practices and the ethanol production process. If a breakthrough is made in commercializing cellulosic or algae-based ethanol, the trajectory could undergo additional radical change. Specific to bio-diesel, H-bio and its process may provide another opportunity for discontinuous change, but it is as yet too early to know.
- In the automotive area, the technology transitions were radical with neat and flex fuel vehicles. Other adaptations which occurred in the intervening periods were more continuous in nature.

- As for bioelectricity, the introduction of high pressure boilers in sugar mills provided significantly improved opportunities for electricity production, yet this has not fully taken root.

G. CHANGE INDICATORS

The transition is gauged next in terms of the shifts in energy mix, costs, societal acceptance, industrial development. These measures will be revisited in the cross-case analysis of Chapter 8. Other indicators on import dependence and carbon savings may be found in the Appendix.

Energy mix/balance

In terms of the energy mix, the share of automotive fuels derived from ethanol shifted from 1% to 41% between 1970 and 2010 – equaling roughly a one percentage point change on average per year. The transition in total transport sector fuels is somewhat smaller, given that ethanol is largely used by automobiles, which only accounts for a portion of transport modalities. Nonetheless, that change reflects an increase from <1% to 17% for the period or less than 1 percentage point on average per year. These transitions are illustrated in Figures G1 and G2.

Figure G1: Shift in Automotive Fuels
(Thousand TOE)

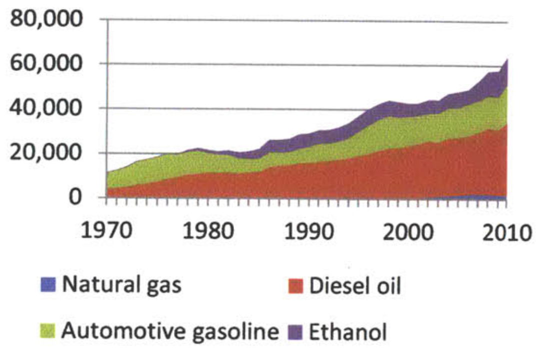
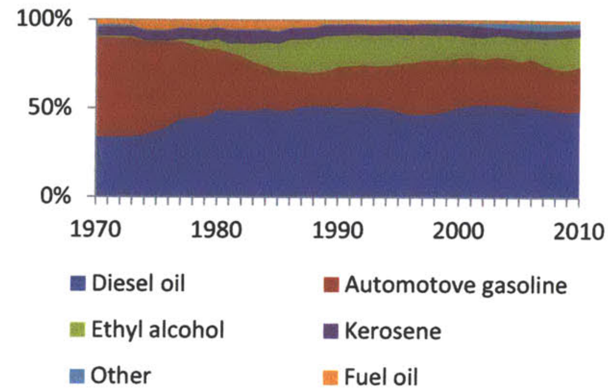


Figure G2: Shift in Total Transport Fuels
(Relative %, includes air, rail, highway, etc)



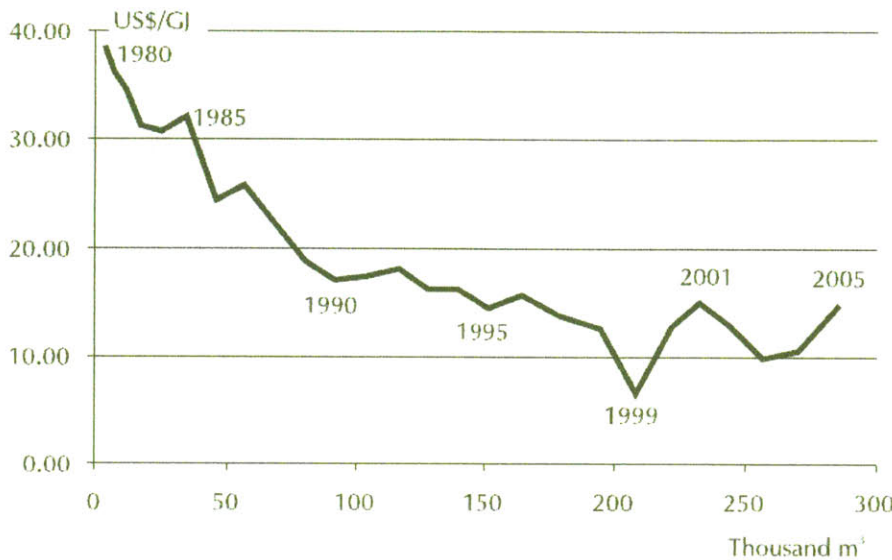
Source: MME data, 2011, for both charts.

Costs

This section considers variants of costs, including the improvement in prices paid to ethanol producers, the prices and learning curve costs of ethanol relative to gasoline (competitiveness), the costs of Brazil sugarcane-based ethanol relative to other types of ethanol, and estimated foreign exchange savings. In short, cost improvements were evident and ethanol is now competitive with market-priced fuels.

Figure G3 shows prices paid to ethanol producers ($/GJ) for ethanol in Brazil between 1980 and 2005. Measured in 2002 dollars terms, the cumulative annual rate of change was a decrease of 1.9% (CGEE and BNDES, 2008).

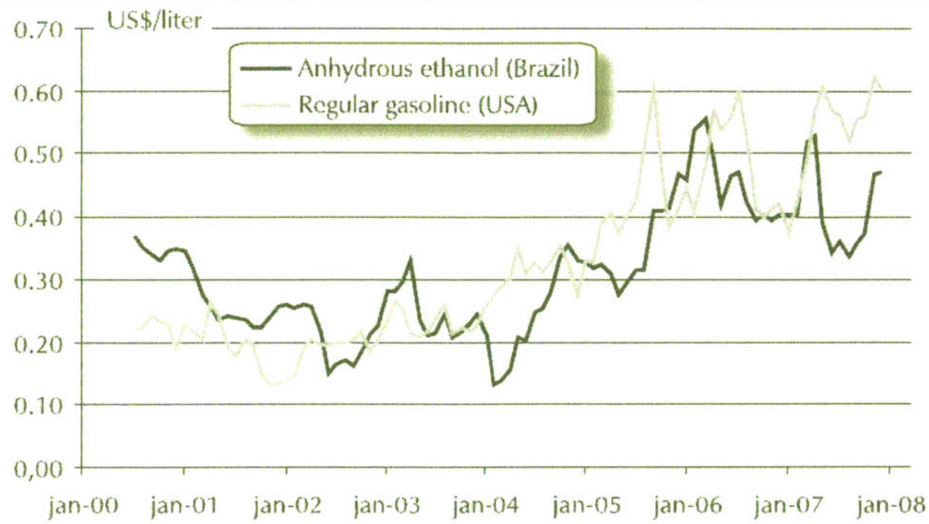
Figure G3: Prices Paid to Ethanol Producers in Brazil ($/GJ)



Source: CGEE and BNDES, 2008, adapted from Goldemberg et al, 2005.

Considered from a slightly different vantage point, Figure G4 shows the prices paid to producers of Brazilian anhydrous ethanol, relative to U.S. gasoline prices, excluding taxes. This indicates that each of the two fuels exhibited some flux and at various points was more cost competitive than the other. For the period of January 2000-January 2008, prices for U.S. gasoline ranged from roughly $0.15 to 0.62/liter, while prices for Brazilian anhydrous ethanol overlapped in a range between $0.17 and 0.58/liter. Since ethanol was not subsidized and its prices were lower than gasoline in certain periods, its competitiveness was demonstrated.

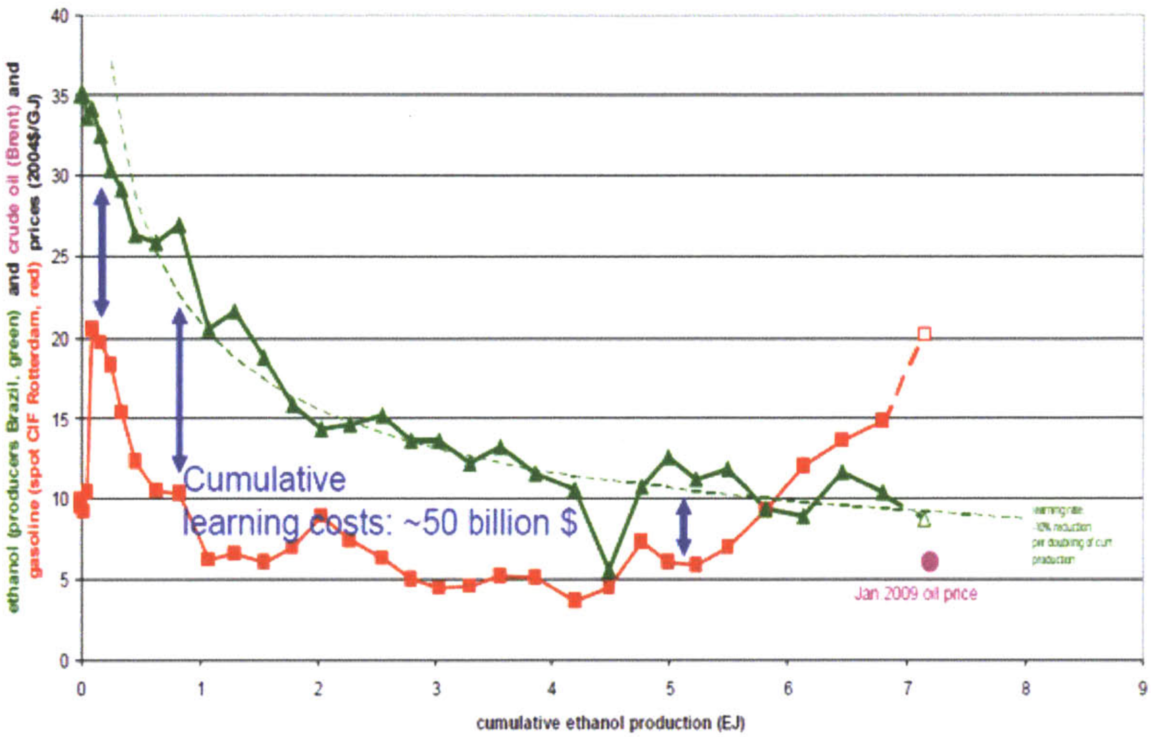
Figure G4: Prices Paid to Producers (ex Taxes) for U.S. Gasoline and Brazilian Anhydrous Ethanol



Source: CGEE and BNDES, 2008, using data from CEPEA, 2008 and EIA, 2008

Another way to consider improvements and competitiveness of biofuels is in the decline of Brazilian ethanol costs over time relative to the Rotterdam gasoline spot price. Figure G5 shows the cumulative ethanol production costs declining to a point that is below that of gasoline. Gains may be attributed to improved seed varieties and agronomical practices, application mechanization/management systems, and gains from scale (Bake et al, 2009; Dal-Bianco et al, 2012). The difference between the gasoline and ethanol cost curves equals what Jose Goldemberg calls the cumulative learning costs (2011).

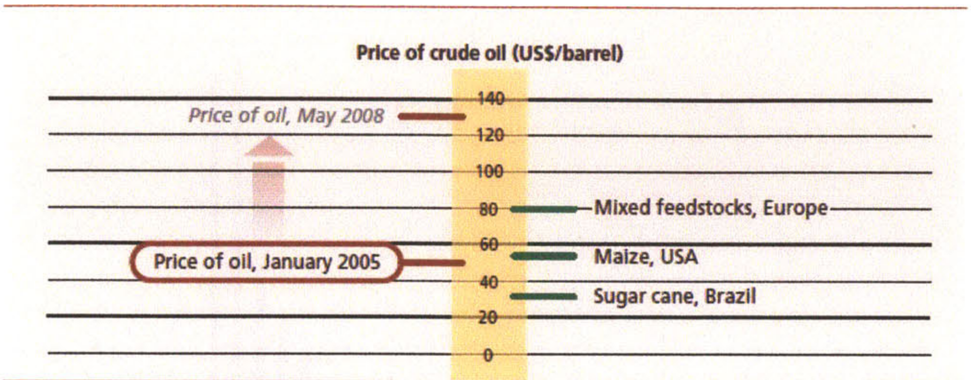
Figure G5: Learning Curve: Costs of Brazilian Ethanol vs. Rotterdam Spot Price



Source: Goldemberg, 2011.

Still another way to view ethanol costs is with different forms of ethanol and relative to oil. Brazil produces the least expensive form of ethanol (Arruda, 2011). Figure G6 shows that in 2005, for example, Brazilian sugarcane ethanol reached a breakeven point in which revenue equaled costs at roughly $33/barrel, while other feedstock reached this balance in the higher $50-80 range. Around that period, oil sold for roughly $50/barrel and more recently reached almost $150/barrel.

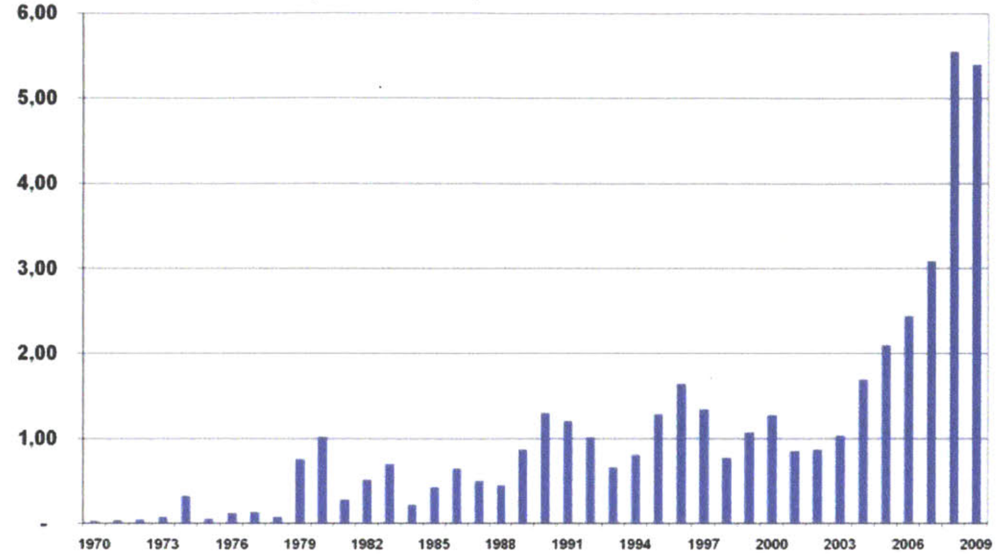
Figure G6: Breakeven Prices for Crude Oil and Selected Feedstocks in 2005



Source: FAO, 2008, based on FAO, 2006.

Finally, cost is considered in terms of savings on foreign exchange savings associated with the displacement of oil imports with ethanol. Ricardo Dornelles, current Director of Renewable Energy in the Brazilian Ministry of Mines and Energy, estimated that $42 billion was saved between 1970 and 2009 with particularly high savings occurring in 2008 and 2009 (Dornelles, 2010; Figure G7). Naturally assumptions will influence this, nonetheless the larger takeaway remains significant.

Figure G7: Foreign Exchange Savings in Brazil due to the Displacement of Oil Imports with Ethanol (Billion, US$)



Source: Dornelles, MME, 2010.

Across all these categories of cost, price and savings, Brazilian ethanol from sugarcane has evidenced very positive improvement and relative competitiveness.

Turing to a question of who paid, a simplified answer would point to automobile drivers who used gasoline particularly in the period from 1975 through to the late 1990s, since taxes on gasoline were used to cross-subsidize ethanol development during that period (Goldemberg, 2011). A more complex answer would point to the industries, actors and fuel types which did not benefit from ProAlcool, since support channeled to sugarcane ethanol was done in lieu of other areas. Another component to the answer lies in the costs absorbed by the national development bank, the fiscal budget and distributors, like Petrobras, which covered initiatives, such as infrastructure conversion. When better access to such data becomes available, this area merits further study.

Societal acceptance

Was there societal acceptance? If not, how was it handled? One interviewee seemed to capture the essence of the choice and a common theme by pointing out that it was not a difficult decision – the Brazilian society had to support ethanol and domestic jobs or take an alternative path which included gasoline rationing, and higher unemployment (Interview, 2012).

Was resistance apparent? It was evident in limited periods with some automobile manufacturers and government ministers, financial institutions, Petrobras, and consumers. Automobile manufacturers were mentioned in interviews as being compelled by the government to produce neat vehicles in the late 1970s (Interviews, 2012-2011). By contrast, others in interviews and published reporting described the situation as one where consensus was formed among auto manufacturers to mobilize the industrial capacity around a more stable fuel (Interview 2012; Chen, 2011). Without question, auto manufacturers had justification for maintaining conventional production lines with internal combustion engine-based vehicles, since ICEs were well-accepted worldwide and neat vehicles were less known, disruptive technology. Yet the persistent side-effects of the global oil shocks were exceptionally high gasoline prices, a rising national debt and a vulnerable balance of payment, as well as uncertainty about prospects for the automobile industry and economy. Here is where neat vehicles, which had been tested in the CTA lab, provided an alternative path to sustain the automobile market. If the auto manufacturers were resistant to the change, they nonetheless worked with the negotiated arrangement, producing neat vehicles latter part of Stage 1.

The introduction of flex fuel vehicles that occurred in Stage 3 was spurred by auto manufacturers, not government.

Various government ministers were also mentioend as not being fully supportive of Brazilian biofuels development (Barzelay, 1986; Interviews, 2010). This should not be surprising since the ProAlcool program in the early years required extensive resource mobilization and political commitment amidst volatile economic times. Large-scale public expenditure, such as that with project financing at rates below inflation, can be risky, particularly during times of high inflation and debt. One interviewee described a meeting before the launch of ProAlcool in which President Geisel told ministers they needed to be 'on board' with the Program or they should not plan to remain in their roles (Interview, 2010). Resistance of ministers appears to have been addressed through the 'normal' mechanisms of political action.

Financial institutions, namely the Banco do Brasil, and the BNDES, were also identified as early resistors of ProAlcool (Barzelay, 1986; Demetrius, 1990).[31] Once the Program was launched, these institutions were known for extensive delays in financing approved projects (Ibid). Given that these finance institutions should have understood the gravity of a widening trade balance and national debt better than most, it is debatable whether delays in processing financial outlays were in the country's best interest. This

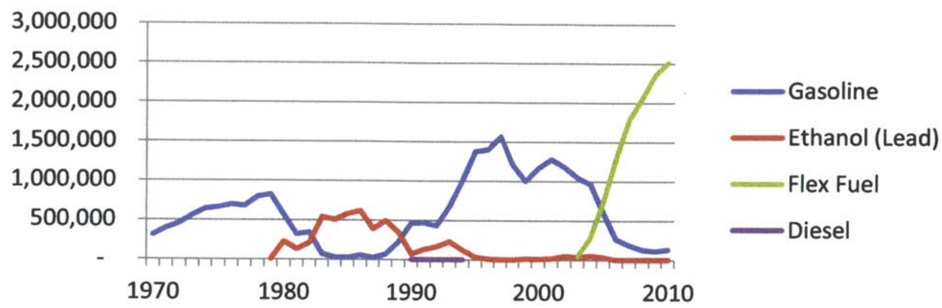
[31] Other financial institutions charged with supporting ProAlcool were Banco do Nordeste do Brasil, and Banco da Amazonia (Decree 76.593). There was no evidence showing they resisted implementation. They were based in regions which had strong need for economic development, so it is not likely (as regional development banks) that they would impede the process.

impedance appears to have changed after 1979 to cooperation, when deepening political and industry commitment to ProAlcool appeared to solidify.

State-owned energy company, Petrobras, was also mentioned as resistant to the biofuels development plan (Barzelay, 1986; Demetrius, 1990, Interviews, 2010). Given that Petrobras' legal charge was to manage liquid fuels for the domestic market and its focus was on oil, the prospect of an emergent biofuels market meant that the company's institutional strength may be diluted from a growing influence of sugar industry actors. Moreover, Petrobras had been created in the 1950s to locate and exploit petroleum reserves and, at the time of ProAlcool's launch, the company had not yet proven itself (Barzelay, 1986). With ProAlcool, Petrobras served as the guaranteed buyer of a set amount of ethanol each year (Ibid; Interviews, 2010-2011). It also appeared to be crucial, albeit somewhat debated, in adapting the transport fuel infrastructure (Interviews, 2010-2012). To this day, it remains engaged in supplying ethanol and now biodiesel.

Acceptance and resistance of automobile drivers to the biofuels transition can in some respects be gauged by the types of automobile purchases. Figure G8 shows a sharp rise in new neat vehicles registrations in the 1980s. Here, policy measures like reductions in registration fees and softer financing terms favorably factored for neat cars relative to traditional ones

Figure G8: Registration of New Automotive Vehicles by Fuel Type in Brazil



Source: ANFAVEA data, 2011, Table 2.5. Note this does not account for vehicles converted from internal combustion to neat technology.

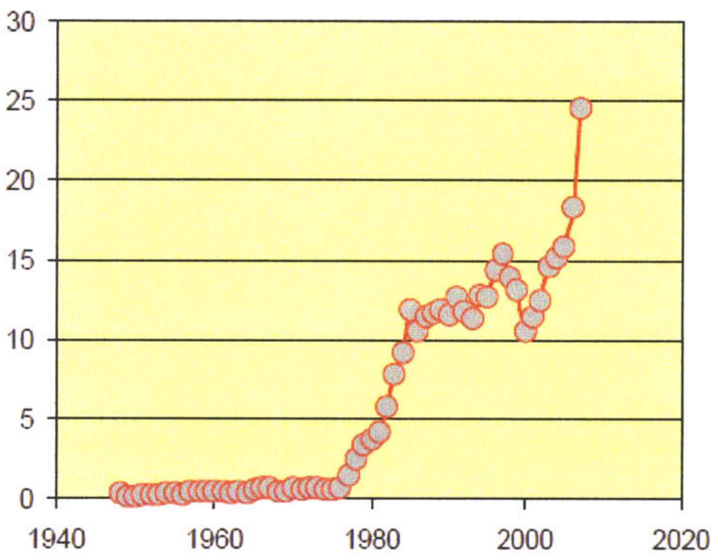
Where consumer acceptance is striking is in two later shifts. A decline occurred in the early 1990s, when consumer confidence in biofuels eroded with a shortage of domestic ethanol (Interviews, 2010). While the supply shortfall was covered by imports, the vehicle favorability was further undermined by government support of less expensive ICE vehicles and the elimination of ProAlcool benefits. A later consumer shift occurred with the introduction of flex fuels in 2003. Here, a near immediate change was evident in consumer automobile interest. Flex fuel technology placed choice in the hands of the automobile driver and drivers responded overwhelmingly in favor of such technology.

Overall, social acceptance appeared to be moderate to significant, enabling the energy systems change with some earlier pockets of resistance. No notable protests occurred and the most obvious resistance was in consumer choices which were allowed to evolve. Less obvious resistance among state actors and institutions appears to have been managed through internal, bureaucratic politics.

Industrial development

Industrial development related to sugar, biofuels and automotive technologies is evident over the course of the course of the past four decades. Fundamentally, the sugar and automotive industries which existed in 1970, were retooled, enabling a scaled production and use of ethanol (Figure G9).

Figure G9: Brazilian Ethanol Production (Billion liters)



Source: Cruz, 2008.

Ethanol production rose by a factor of 45 during the period with Brazil becoming a top global ethanol producer and exporter (Datamonitor, 2010; FO Licht, 2011). Currently, the Brazilian biofuel industry is the second largest in the world in production terms (Ibid). As of mid-year 2011, Brazil produced approximately 30% of the global supply (Eco-energy, 2011). For the period 2000-2010, Brazil exported more than the United States, the current top producer of ethanol (Ibid; Datamonitor, 2010). As of August 2010, 432 mills operated in Brazil with 251 serving as dual-purposed units that produce ethanol and sugar (UNICA, 2010). Another 162 units are ethanol distilleries (Ibid). All of the 432 units are self-sufficient in terms of producing and using thermal energy and electricity (Ibid), meaning they combust feedstock like residual bagasse to power their plants.

Foreign participation has grown in the Brazilian ethanol-sugar market. In 2009-2010, 22% of the mills were owned by foreign capital relative to 7% in 2007-2008 (Ibid). In market analysis, the Brazilian biofuels industry is considered very well-established relative to other countries (Ibid). Recently, Brazil has served as a leader in technology transfer related to biofuels by offering training domestically and abroad (Ministry of Foreign Affairs, 2010, Interviews, 2010-2011). It is a founding member of the Global Bioenergy Partnership (Hira, 2011).

Turning to the automobile industry, its specialization in accommodating biofuels blends with vehicles design distinguished it over the course of four decades. The introduction of flex fuel technology tailored to the Brazilian market in 2003 has proven to be a commercial success (Kamimura and Sauer, 2008; ANFAVEA, 2011a). In an industry which produced 3.4 million light weight commercial vehicles and exported $12.3 billion worth in 2011, flex fuel has become a dominant design (ANFAVEA, 2012a). In 2011, 83% of the new passenger and light commercial vehicles registered in Brazil were flex fuel (ANFAVEA, 2012a). The accumulated fleet since 2003 is estimated to equal 15.3 flex fuel vehicles (Ibid).

In terms of the automotive industry, Brazil also has the largest share of flex fuel autos worldwide, equaling what is estimated to be 16% of the global share (UN Energy, 2011). As of June 2011, there were roughly 25.1 million ethanol-FF vehicles sold globally and concentrated in a few markets (Ryan, 2007). Brazil led with 14.3 million (ANFAVEA, 2011a and 2011b; Abraciclo, 2010-2012), followed by the U.S. with 10 million (Slater, 2011) and Canada with roughly 600,000 (Young, 2008). Currently, there are roughly 80 models of flex fuel auto and light truck vehicles available in the Brazilian market, produced by 12 automobile manufacturers, plus 4 models of flex fuel motorcycles (Directa da Usina, 2011; UNICA, 2011). Flex fuel technology has continued to evolve with improved fuel compression, better fuel economy, less emissions and improved cold start functionality (Royal Society, 2008; Olmos, 2007). Fuel economy, for example, has changed from a range of 25-35% less than gasoline powered ICEs to 20-25% (Ibid).

H. CONCLUSION

Brazil's biofuels conversion reflects targeted industrial policies in the early years for agro-energy and automobiles to meet energy, economic and environmental objectives. Taken together, efforts reconfigured existing markets, industry and infrastructure, enabling a by-product of the sugar industry to become a mainstream transport fuel.

The top-down approach of the Brazilian government in the 1970s and 1980s with a blend of supportive policies provided critical impetus and structure for the early phase of biofuels development since 1970. The energy system architecture and market functions which developed, then sustained -- even after substantial retrenchment tied to deregulation and economic challenge.

The phenomenon of dual use is an interesting aspect of the Brazilian biofuels trajectory. The substitutability of sugar versus ethanol in agro-industry production, ethanol versus gasoline in fuel consumption, and now bagasse waste for bioelectricity versus the use of waste as a feedstock in cellulosic ethanol has given Brazilians valued options and adaptation pathways within changing contexts (Cortez, 2010; Goldemberg, 2010).

Significantly, incremental and disruptive innovations occurred throughout the four decades in ethanol production, automotive technology and bioelectricity. Innovations which incubated during the 'dormant years of the 1990s,' particularly advances in flex fuel technology and agriculture, were instrumental in defining a second generation of robust biofuels development during the last decade. In contrast to the government's strong hand in the earlier growth period, the recent resurgence in biofuels is now powered by a more independently-driven private sector

APPENDIX

Brazilian Energy Transition Timeline

1970

- Ethanol equals less than 1% of the total transport and automotive fuels in Brazil

1973-1974

- Oil Embargo/first oil shock

1975

- June – President Giselle visits Professor Stumpf's lab where tests of hydrous and anhydrous ethanol on engines were conducted
- November - ProAlcool Program launched, including:
    - A target of 0.8 billion gallons of ethanol (3 billion liters) by 1980, primarily via blending
    - Mandate for Petrobras to purchase ethanol at set price and blend w/ gasoline

1975-1985

- Robust growth in ethanol production

1979

- Second oil shock, Iranian Revolution
- Ethanol production goal raised to 2.8 billion gallons (10.7 billion liters) for 1985
- Mandated installation of 100% only ethanol pumps at gas stations
- Price of 1 liter of ethanol set at 59% of 1 liter of gasoline
- The government provides low interest loans to agriculture to produce ethanol
- The government and auto industry reach agreement that industry will produce mostly lead vehicles

1980

- Hydrated ethanol and neat vehicle (100% ethanol) sales begin

1986

- Alcohol vehicle sales peak at approximately 90% of new light vehicles
- Collapse of world oil prices

1986-2000

- Flat/incremental growth or decline in ethanol production

1989-1990

- Increase in ethanol prices
- Removal of some ethanol subsidies
- Decline in ethanol production and supply shortages resulting in ethanol imports
- Alcohol vehicle sales decline substantially

1990-2000

- Deregulation of energy and sugar markets

1991

- ProAlcool officially ended although, CINAL maintained some functions

1993

- Blending set at 22%

1994

- End to universally set fuel price

1997-1999

- Subsidies end

1998/9-2002

- Lead vehicle sales end

- Ethanol prices liberalized

2002-2004

- Biodiesel specifications are set

2003

- Flex fuel vehicle sales begin
- Blending set at 25%
- Surge in oil prices

2004

- Brazilian sugarcane-based ethanol is cost-competitive with gasoline
- Biodiesel Program (CNPB) is launched

2006

- Brazil attains net oil independence

2008

- Biodiesel blend of 3% required
- Public Auctions for biodiesel occur

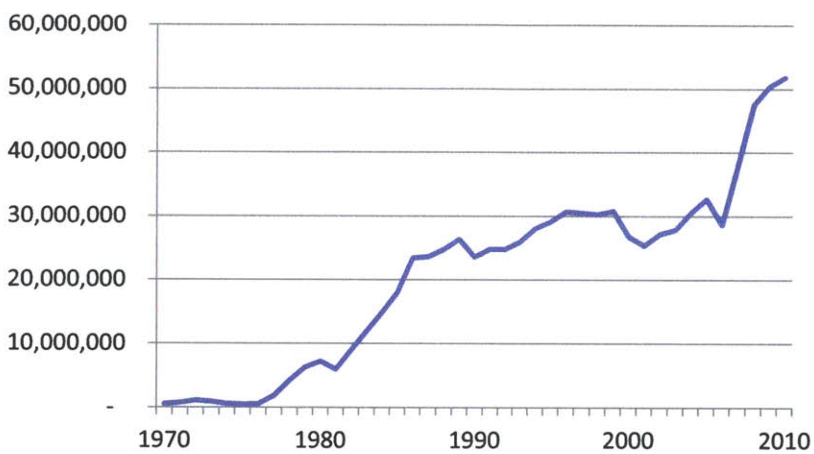
2011

- Ethanol equals roughly 17% of total transport fuels and 41% of automotive fuels in Brazil.

Carbon change

This study estimates avoided carbon with coefficient analysis. Based on this methodology (see Figure A1 note), 847.7 billion t CO_2 were cumulatively displaced in the period between 1970 and 2010 which equals 21.2 million t CO_2 on average per year. Figure A1 illustrates the avoided CO_2 emissions from substitution of hydrous and anhydrous ethanol for gasoline.

Figure A1: CO_2 Emissions Avoided by Displacing Gasoline with Ethanol *(t CO_2)*



Source: Ethanol data, Ministry of Agriculture, 2012, citing PPE/MME

Note: This assumes 1 liter of hydrous ethanol = 0.7 liters of gasoline (E100 Engine) and 1 liter of anhydrous ethanol = 1 liter of gasoline (E25 Engine) (Macedo et al, 2004). It also assumes 2.82 kg CO_2/liter anhydrous ethanol, 1.97 kg CO_2/liter hydrous ethanol (Ibid). 1000 kg = metric ton (t). This does not factor for variation in land use or production processes.

Import Dependence

In terms of import dependence, Brazil experienced a substantial change in its petroleum imports and overall energy import reliance. Figure A2 shows the change in imported petroleum as a share of total petroleum used. Petroleum imports were 77% of that used in 1973 at the time of the first oil shock, peaking at 85% in 1979, and then declining to negative numbers, implying exports. This change tracks closely with Figure A3 which shows the change in total energy import dependence for Brazil for the same period. While these trajectories reflect the low carbon substitution of ethanol for gasoline, they also represent other critical changes, particularly the dramatic shift in Brazil's oil production to a status as a major Non-OPEC oil producer (MME, 2011).

Figure A2: Brazilian Petroleum Deficit
(Petroleum Imports as a % of Petroleum Used)

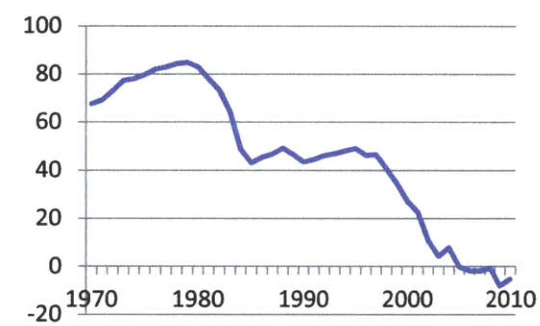
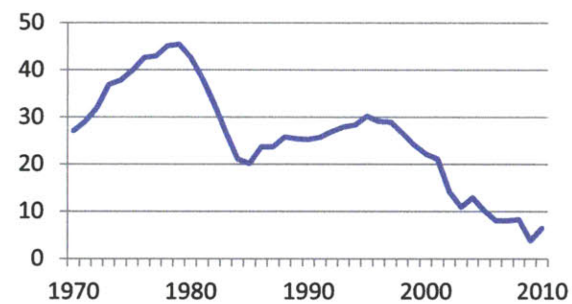


Figure A3 Total Energy Import Dependence
(% of Total Energy Demand)



Source: MME, BEN 2011 for both charts.

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Chapter 5

Danish Wind Power: Alternating Currents

> *You can discuss [energy options] as much as you want, but atomic power is what you're going to get….*
>
> – Director of Danish electricity distribution company ELSAM, mid-1970s[1]

A. INTRODUCTION

The power of wind has been tapped for centuries in sea transport, irrigation and agriculture (Wiser et al, 2011; Gipe, 1995). History shows that wind energy was being used for boat propulsion on the Nile River as early as 5,000 B.C. (Department of Energy/DOE, 2011). By 200 B.C., it was employed to pump water in China and grind grain in Persia and the Middle East (Ibid). In recent years, wind has increasingly been used to generate electricity. Since 1990, for example, global wind energy capacity has roughly doubled every 3.5 years (World Energy Council/WEC, 2010). In 2012, wind capacity is projected to deliver 2.3% of global electricity consumption and by 2021 could meet 8% (BTM, 2012).

When considering country examples of wind power progress, Denmark stands apart as a leader in wind energy utilization, as an international hub for wind technology development and manufacture, and for setting key standards and planning practices in place (Renewable Energy Network 21/REN21, 2011; Danish Wind Industry Association/DWIA, 2012; Gipe, 1995; Mills and Manwell, 2012; IEA, 2011a; Meyers, 2003 and 1995). This chapter explores how Denmark drew upon historical knowledge of

[1] Jorgensen and Karnoe,1995.

wind power in small-scale distributed generation on farms, school laboratories, and in rural power plants to produce a world class industry. The case highlights the role of activist citizens; governmental policy steering; and incremental learning in technology change.

Like the other case chapters, this chapter begins by discussing basic characteristics of the low carbon energy in focus. Wind energy and its technologies are outlined. This is followed with a broad overview of the Danish wind energy transition. Major innovations and adaptations, drivers and barriers, and performance indicators are then considered. The chapter concludes by discussing conditions in the enabling environment.

B. BASICS of WIND POWER and TECHNOLOGIES

Wind is produced from solar flux on the Earth's irregular surface (Springer Verlag, 2006). As solar radiation enters the Earth's atmosphere, wind is generated through uneven heating of the earth's surface (Wiser et al, 2012; and Wiser et al, 2012, citing Hubbert, 1971; Energy Information Administration/EIA, 2011). Pressure differences produce air particle shifts which, in turn, generate wind flows that are shaped by the Earth's rotational flow, geography, and temperature gradients, among other factors (Wiser et al, 2012, citing Burton, et al 2001). In order to harness wind energy, the kinetic energy embodied in its motion must be converted to mechanical power for processes like pumping water or be transformed into electricity with a generator.

Wind is prevalent in varying strengths virtually everywhere (Ibid; Archer and Jacobson, 2005). Recent estimates of global wind resources indicate that a potential exists for more than forty times the current electricity consumption, or more than five times the total use of energy worldwide (Lu et al., 2009).[2]

Resource characteristics of wind differ by location and time. Like basic topography, wind quality often varies within a given region. It can have different availability over various time scales, including sub-hourly, daily, by season and in terms of inter-annual flux (Wiser et al, citing Van der Hoven, 1957, etc). Given this, wind must be managed in a way which differs from non-variable energy sources (discussed below).

The simple power of wind is measured by the cube of its speed, so each time the average speed of wind doubles, power increases by a factor of 8 (European Wind Energy Association/EWEA, undated). Subtle differences in speed can then have large effects on power output. If, for example, average wind speed increases from 6 meters per second (m/sec) to 10, wind power output could increase by 130+% (Ibid).

The fastest wind velocities are generally found at sea, on hilltops, and open coastlines (Ibid). To effectively tap wind's potential, utilization must account for wind strength,

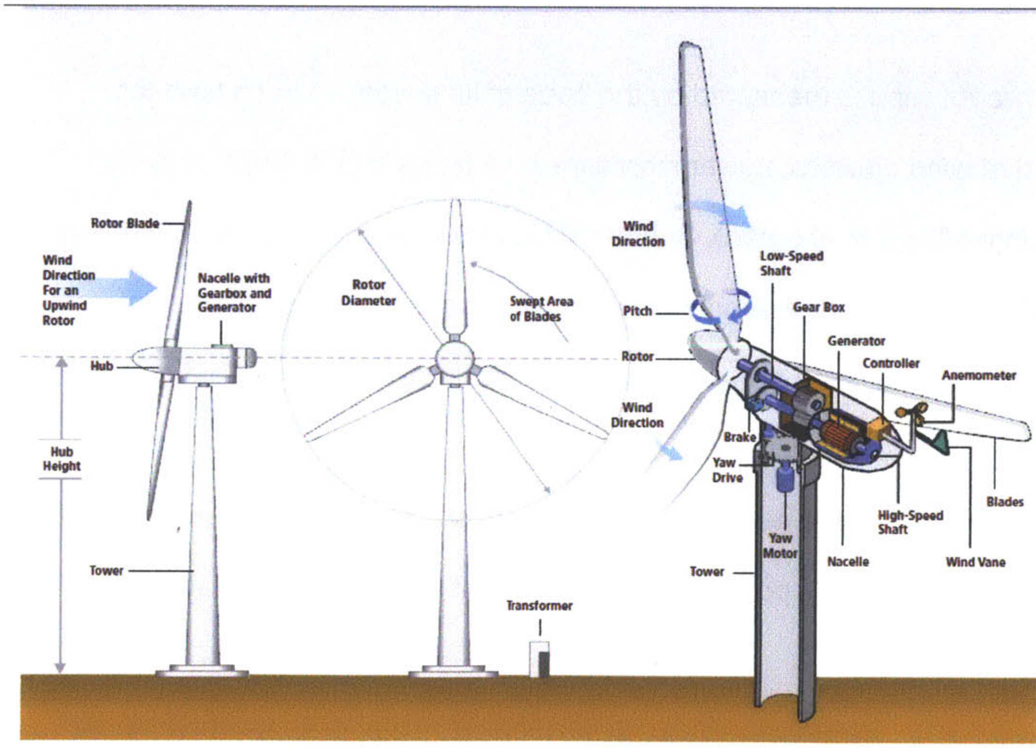
[2] This includes onshore and offshore wind, modeled at a 20+% capacity factor with a 100 meter hub height (Lu et al, 2009).

direction and frequency of flows,[3] which have a fundamental bearing on the performance and economics of wind generation at a given site (Ibid).

Turbine Technology and Design

The basic functioning of a wind turbine mimics a fan working in reverse. Rather than utilizing electricity to produce wind, wind instead passes over the blades of a rotor that, through a shaft, spins a generator to produce electricity (DOE, 2011). This operation occurs when wind flows cause lift to turn the blades (Figure B1).

Figure B1: Basic Components of a Horizontal Axis Wind Turbine with Gearbox



Source: Wiser et al, 2012. [4]

[3] Mean wind speed directional data, gust information, and data on seasonal, annual and height variation are typical parameters to gauge (Tiwari and Ghosal, 2007).

The torque (i.e. turning force) on the rotor blades is a function of the wind speed, density of air and rotor area (WindPower, 1998). Density or heaviness of air is measured by the mass per unit of volume. Essentially, the heavier the air density, the more energy a turbine can capture (Ibid). The rotor area determines how much energy can be harvested from the wind in a location by a given turbine (Ibid).

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[4] Select components include:

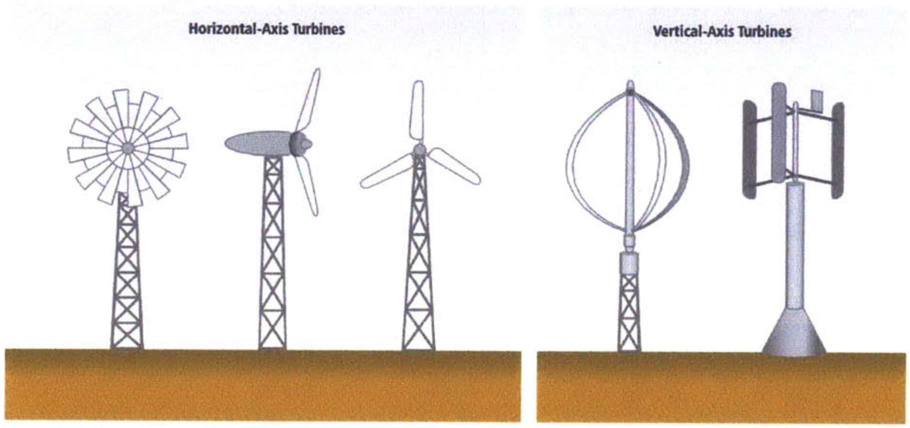
- An **anemometer** gauges wind speeds.
- The **controller** starts and stops a turbine at cut-in and cut-out speeds.
- A **drive-train** generally houses a gearbox and a generator.
- The **gear box** connects low and high-speed shafts, allowing a stepped increase of rotational speed to a range that is conducive for producing electricity.
- A **nacelle** consists of the gearbox, shafts, generator, controller and brake.
- **Pitch** is blade positioning to control wind.
- **Pitch and stall-control** are ways to control a turbine. With pitch-control, an embedded anemometer tracks wind speed and conveys instructions to optimize efficiency through blade adjustment. With stall-control, blades are attached in a fixed position with a design for maximal power output and equipment protection. Pitch-regulated turbines are generally more efficient and stall-regulated ones are typically more reliable with less design complexity (Horizon Wind, 2011).
- The **rotor** consists of the blades and the hub. Upwind and downwind turbines position the rotor in relation to the wind flow. In upwind models, the rotor is located at front of the unit and is oriented by a **yaw drive** mechanism. In downwind models the rotor is positioned at the back of the unit, so a yaw device is not necessary.
- The **tower**, typically made of steel or concrete, serves fundamentally as a stand for the nacelle and rotor.
- **Weather vanes** gauge wind direction.

Source: DOE Wind Program (2011), unless otherwise noted.

Basic Model Types

Two basic models of wind turbines exist - the vertical axis (VAWT) and horizontal axis (HAWT) designs, distinguished by the direction of the rotating shaft (Figure B2).

Figure B2: Types of Wind Turbines



Source: Wiser et al, 2012, referencing South et al, 1983.

Today's wind turbines typically reflect the HAWT design with propeller-like blades sitting on a rotating shaft that runs parallel to the ground. The rotor in these models is often located on the front or upwind side of the tower. Such models can measure the height of a 20 story building (EIA, 2011).

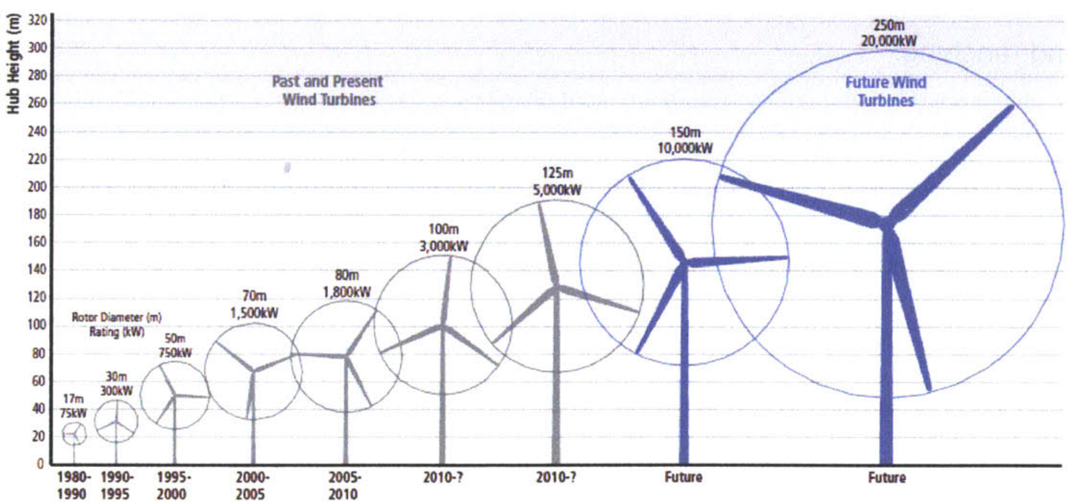
The less common VAWT design has blades oriented from base to top. A typical version is the Darrieus design, which is a 2-bladed model resembling an egg beater. VAWTs often attain a length of 100 feet and width of 50.

Most contemporary turbines operate with the 3-bladed design, yet single, two and 3+ bladed designs are also used. Some of today's largest blades are longer than a football field (Ibid).

Commercial Turbine Size and Development Directions

Modern, commercial manufacture of wind turbines is often linked to the early 1980s. Since then, models have increased in size from 75 kW to 2-5 MW (2,000-5,000 kW) (Figure B3). Today's units frequently range from 100 kW to 3MW (Ellenbogen et al, 2012). Depending on siting conditions, a 1 MW turbine can produce electricity for 650 households (EWEA, undated). Research and development focusing on wind technology size now centers on 5+ MW models (EWEA, 2009a; Interviews, 2011-2012).

Figure B3: Growth in the Size of Typical Commercial Wind Turbines



Source: Wiser et al, 2012, design by NREL.

Today's wind turbines are designed to be quite reliable with an operational availability of 98% (EWEA, undated).[5] In a 20-year operational life of a wind turbine, the turbine can function continuously and unattended with minimal maintenance for roughly 120,000 hours of active operation (Ibid). By contrast, a car engine typically has a design life of roughly 6,000 hours of operation (Ibid). Development efforts currently include material and design optimization of rotor blades, controller capabilities, alternative drive train configurations, network operator requirements, among others (EWEA, 2009).

Modularity, Multi-purposing, and Scale

Key attributes of wind power plants include modularity and the potential for multi-purpose use of space. Turbine modularity enables quick installation as single units, clusters, or large-scale wind farms. The relatively non-intrusive nature of wind turbines means that land between the sited units can be simultaneously used for purposes, like farming and ranching.

Contemporary wind farms can consist of 300+ turbine units, covering an expanse of several hundred square miles (EWEA, undated; EWEA, 2009). Some of the largest onshore wind farms include the Gansu Wind Farm in China (5,000+ MW) and the Alta Wind Energy Center in the United States (1,020 MW). By comparison, fossil fuel plants are often 500-1,000 MW and nuclear plants are usually 1,000-1,500 MW. The largest

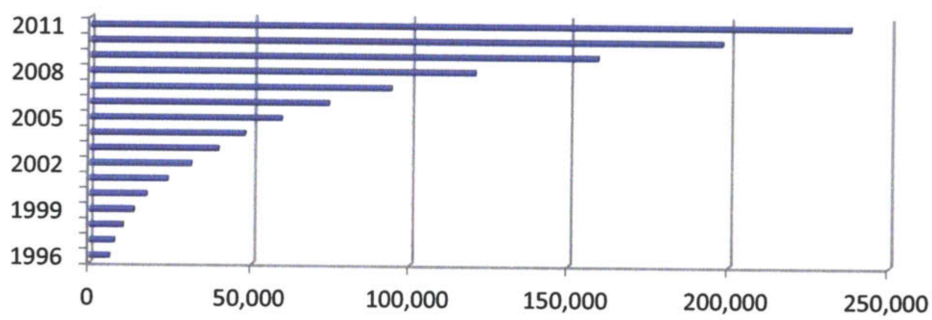
[5] The availability factor of a power plant gauges the amount of time that the plant is able to produce electricity in a given period divided by the total time of the period. Availability factors are a function of the fuel type, plant design and operational approach, so vary widely. Thermal power plants, like coal, nuclear and geothermal plants, have availability factors of 70-90%. Natural gas plants tend to be in a range of 80-99%.

offshore wind farm currently is Walney Wind Farm in the United Kingdom (367 MW). Based on current projects and planning, larger projects are underway (Global Wind Energy Council/GWEC, 2012; Interviews, 2011-2012).

Onshore and Offshore Wind

At the end of 2011, installed wind capacity was 237,669 MW worldwide, involving commercial installations in 75 countries (GWEC, 2012, Figure B4).

Figure B4: Global Cumulative Installed Wind Capacity (MW)



Source: GWEC, 2012.

Onshore wind technology has a fairly well-proven track record. In good locations, its generated power is competitive with newly built, conventional power plants under conditions with good wind resource, particularly where the cost of carbon is internalized (Arvizu et al, 2012; IEA, 2009b).

Offshore wind technology is at an earlier stage in commercialization, yet the wind resource is typically much more powerful. Investment costs for offshore wind projects are roughly twice that of onshore wind investment, yet the quality of offshore wind resources can be 50% better relative to onshore wind resource, due to stronger and more frequent winds (IEA, 2009b; EWEA, undated). Recognizing the stronger power production opportunity and rugged conditions of the sea, offshore wind turbines need to be more resilient than their onshore counterparts. Currently, offshore wind represents a small fraction of the installed capacity to date, nonetheless is key to a number of regions' energy plans, so market expectations are high (EWEA, 2009).The growing market for offshore wind raises new challenges in the logistics of manufacture, testing, transport, installation and maintenance (EWEA, undated). Special approaches and vessels for installation have been developed and the means of access to offshore turbines, once operating, is an important factor in terms of cost, safety and availability (Ibid).

Wind Resource Assessments and Technology Indicators

Wind resource assessments are typically done to evaluate the resource potential or forecast expected wind power production in a given location. Forecasts are used for trading, scheduling and power dispatch in the power sector. By contrast, spatial assessments with maps or atlases are done to determine optimal locations for siting wind turbines and to estimate annual energy output (Krohn, 2002b).

Wind assessments are best developed through on-site measurements employing anemometers and weather vanes that can be enhanced with data from nearby weather stations (EWEA, 2009a). In conjunction with this or, as an alternative, computer modeling is used, accounting for topography, ground surface cover, and elevation (Ibid).

Resource classes are assigned, accounting for wind speed variability, average wind speed and average air density (Sawin, 2001). Using the resource class and other parameters, wind potential is estimated in terms of power generation. Estimates for the offshore wind potential in the European Union, for instance, indicate a resource up to 3,000 TWh, which exceeds the total electricity consumption there (EWEA, undated).

Table B1: Classes of Wind Power Density at 10 and 50 meters

Wind Power Class	10 m (33 ft)		50 m (164 ft)	
	Wind Power Density (W/m2)	Speed m/s (mph)	Wind Power Density (W/m2)	Speed m/s (mph)
1	0-100	0.0-4.4 (0-9.8)	0-200	0.0-5.6 (0-12.5)
2	100-150	4.4-5.1 (9.8-11.5)	200-300	5.6-6.4 (12.5-14.3)
3	150-200	5.1-5.6 (11.5-12.5)	300-400	6.4-7.0 (14.3-15.7)
4	200-250	5.6-6.0 (12.5-13.4)	400-500	7.0-7.5 (15.7-16.8)
5	250-300	6.0-6.4 (13.4-14.3)	500-600	7.5-8.0 (16.8-17.9)
6	300-400	6.4-7.0 (14.3-15.7)	600-800	8.0-8.8 (17.9-19.7)
7	400-1,000	7.0-9.4 (15.7-21.1)	800-2,000	8.8-11.9 (19.7-26.6)

Source: NREL, undated.

When considering the power of a specific wind turbine (or power plant), the rated power output reflects the upper limit of electric power generation. This is represented typically as kW or MW. With wind turbines, this in effect aligns with the cut-out speed of a turbine – the point at which a turbine will stop for security reasons at high wind speeds.

The capacity factor for wind power, as with other types of power plants, is the ratio of actual power produced in a given period relative to the plant unit's full capacity. Typical capacity factors for various types of plants are: wind 20-40%; biomass 25-80%; geothermal 45-90%; solar photovoltaic 6-20%; hydropower 20-90%; nuclear 60%-

100%; and large coal 70-90% (WEA, 2004; Renewable Energy Research Laboratory, undated; Kagel et al, 2007).

When evaluating wind power in regional plans, indicators often include the generated capacity or generation, the average annual capacity factor, installed capacity, and the share of total electricity. The generated capacity represents the amount of electricity produced. The average annual capacity factor is a function of the area wind resource and the way turbines are configured. This indicator is dependent on the hub height of the turbine as well as the generator capacity divided by the swept rotor area (W/m^2) (Energinet and Energistyrelsen, 2012). Installed capacity represents the full load that a turbine, project or region is technically able to produce. The share of total electricity derived from wind power, as the name suggests, is the ratio of wind generation for a given period divided by all electricity produced for that period.[6] Installed capacity is useful for gauging wind power infrastructure at a project or country level, whereas the share of wind power in total electricity gauges wind's contribution to the overall electricity mix.

[6] This is used interchangeably, here, with wind intensity or wind penetration share of total electricity,

In some reporting, this measure is normalized against a wind index which serves as a baseline for the average wind resource over a period of time.

Grid integration

As an intermittent source of energy, wind power is managed differently from fossil fuel-powered plants. The flexibility of grid systems allows wind variability to be smoothed.

What determines a grid system's flexibility depends on factors like forecasting, spatial dispersion and aggregation, and the use of interconnections, among other elements. With forecasting, accurate predictions of expected wind power output, particularly in increments specific to generation and transmission scheduling, allow grid operators to manage wind generation fairly effectively (EWEA, 2009). If wind producers are able to provide forecasts close to real-time (i.e. shorter gate closures), they are able to submit more reliable information (EWEA, 2010). In terms of spatial management of wind power, wind turbine output can be aggregated across a wide geographic expanse, allowing a natural leveling of variation. Use of interconnections (i.e. links between two networks) allows not only geographic smoothing, but trade across networks. With increased levels of interconnection, grid operators are able to leverage the aggregate potential of reserves, generation mixes and geography across larger physical areas. This approach enhances the ease of smoothing power supply and demand (with or without wind inputs) and can reduce balancing costs. Finally, network optimization with a diverse mix of energy types, including dispatchable renewables like hydropower, geothermal energy, biomass, waste, solar thermal electricity; reserve availability; storage/demand-side options; and conducive market rules, allows large-scale wind to be managed (EWEA, 2009; Lovins, 2011).

Not unlike other types of power generators, certain conditions must be met, when wind turbines are connected to the grid. Output must synchronize with the power on the grid system in terms of voltage, current, frequency and amplitude. Codes designate technical requirements for connection of a power plant (turbine unit or otherwise) to the grid. Such requirements, like those specific to tolerance, protective devices, active and reactive power, and power quality are evolving as greater amounts of wind are used (EWEA, 2009). These also can address newer functions, like active control and provision of grid support services (Ibid).

Environment

Wind power projects have a much smaller environmental footprint compared to conventional power plants. Wind plants have no direct emissions in their use, although some emissions exist in turbine manufacture, transport, installation, and decommissioning. They also produce minimal waste, use negligible amounts of water, and do not involve mining or drilling (Wiser et al, 2012). Because of these features, the lifecycle effects of wind generation relative to other types of fuel generation measure up quite favorably (Energinet et al, 2010; EWEA, 2009).

Broadly speaking, ecological considerations of wind projects focus on: sound and shadow flicker; impacts on birds and bats; and effects on marine life in the case of offshore wind; among other qualities.[7]

[7] Because of the highly subjective nature of aesthetic considerations, like visual preferences, this study does not cover them for any of the technologies.

Sound in relation to wind projects generally is a function of turbine design, distance from structures and listeners, placement of the turbine, proximate terrain, and atmospheric conditions (Ellenbogen et al, 2012).[8] Sound from wind turbines can be audible or sub-audible, and may be a nuisance, if not managed properly. When hub height wind speeds are high and ground level wind speeds are low, sound emissions may be greater (Wiser et al, 2012). In this set of conditions, the absence of ground level ambient sound from wind, combined with higher sound levels of hub height winds can produce higher audibility (Ibid, citing van den Berg, 2004, 2005, 2008 and Prospathopoulos and Voutsinas, 2005).[9] Major efforts have been made over time to reduce sound levels of wind turbines (Wiser et al, 2012).

Shadow flicker, the rapid changes between shadow and light that occur when blades rotate between the sun and an observer, depend in the location of the observer relative

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[8] Upwind and downwind turbines have different sound attributes, since the blade and wind speed interaction occurs differently behind the tower as opposed to in front of it (Ellenbogen et al, 2012).

Terrain and atmospheric conditions influence in the sound dynamics of wind turbines, as sound refraction can be shaped by hillsides, temperature gradients, and atmospheric absorption, among factors (Ibid).

[9] Some claim that the sub-audible sound of wind turbines links to health effects ((Wiser et al, 2011, citing Alves-Perreira and Branco), however a range of studies and reports have not found sufficient evidence to support this (Ellenbogen et al, 2012; Wiser et al, 2012, referencing various). Guidelines by the World Health Organization and U.S. Environmental Protection Agency are generally believed to be sufficient to avoid direct physiological health effects, (Wiser et al, 2012, citing EPA1974; WHO 1999, 2009).

to the turbine and the time of year (Ellenbogen et al, 2012).[10] Such flicker can exist at ranges of 1,400 m or less from a turbine with proper siting reducing the effects.

With birds and bats, collision fatalities are a concern when siting new projects. Scientific understanding of the risks associated with this phenomenon is still evolving (Clarke and Ricci, 2003) and much depends on the species, the locational character of turbine siting and the turbine(s) (Wiser et al, 2012). Effects also can vary across stages of installation, operation and decommissioning.

As offshore wind power increases, marine life effects are being studied pre and post-construction. Similar to conditions related to birds and bats, environmental effects are a function of the species, the locational character of turbine siting and the turbine(s), and can vary between stages. Adverse impacts may relate to disruption, sounds and vibrations, and electromagnetic fields (Wiser et al, 2012). Positive effects can include the creation of new breeding grounds and shelters, and artificial reefs related to the physical structures of the wind turbine foundation (Ibid). Effects do not appear to be large, nonetheless further study is warranted.

To balance the positive character of wind power's low environmental footprint with negative effects, the key is in planning, permitting, production and monitoring to minimize adverse impacts (Clarke and Ricci, 2003).

[10] Shadow flicker frequencies of wind turbines are proportional to the rotational speed of the rotor multiplied by the blade number. This typically falls between 0.5 and 1.1 Hz for large turbines (Ellenbogen et al, 2012).

Economics of Wind Power

The economics of wind power generation, like other power plants, must factor for the costs of investment, operation and maintenance (O&M), financing, the annual energy production, and the assumed economic life of a plant, among other considerations (IEA Wind Task Force 26, 2011; Wiser et al, 2012, see Appendix for Cost and Financing).[11] These elements allow one to calculate a levelized cost of energy, providing a form of comparison for energy projects across varied fuel types and plant life (Chapter 1, Appendix). If levelized cost is considered alongside economic support policies, power market rules, and the costs of alternatives, the economic feasibility of projects can be appraised (IEA Wind Task Force 26, 2011; Wiser et al, 2012). A 2010 IEA study surveyed a range of assessments of power plant costs, finding that hydropower reflected the lower bound of levelized costs around $45-240/MWh and solar photovoltaic energy reflected the upper bound at $674-1,140/MWh)[12] with wind power (onshore and offshore), reflecting a mid-range of $91-181/MWh (Ibid and IEA, 2010e). Economic support policies and power market rules naturally will vary depending on the location.

From the early 1980s through to 2004, investment costs for wind power underwent a very steady decline (IEA, 2009b). However, international cost trends increased from 2004 to 2009, due to the rising price of turbines (larger models), supply constraints on

[11] Decommissioning is another cost, but is not typically expected to be considerable for wind power plants (Wiser et al, 2012).

[12] More recent price declines in solar energy and unconventional gas were not fully included.

materials (i.e. copper, steel, carbon fiber, cement, etc), pressures on labor costs, currency valuations in manufacturing countries, and the outmatching of demand with supply (Wiser et al, 2009, see also Wiser et al, 2009, citing Blanco, 2009). A recent study by the International Renewable Energy Agency found positive developments in wind power, namely the costs of wind generation in the best sites of North America was $0.04-0.05 in 2010, "competitive with or cheaper than gas-fired generation even in the so-called 'golden age of gas' " (International Renewable Energy Agency/IRENA, 2012). In addition, the costs of wind turbines for countries like China are 50-60% cheaper than North America (Ibid).

Another way to consider the economics of wind is in terms of the energy costs of production vs. earnings from energy generation, and payback period. Studies indicate that a modern wind turbine pays for itself in a very short period of time, producing 35 times more energy than what was required to produce it (Danish Wind Turbine Owners Association/DWTO, 2012). Recent analysis of energy payback periods for wind turbines also indicate that a 3 MW offshore wind turbine is associated with a 6.8 month payback window, while that for a similar onshore turbine is 6.6 months (Ibid, citing Vestas, 2007). Analysis of the Horns Rev 1 wind farm in Denmark, an offshore project brought on-line in 2002, shows that the payback for its 2 MW turbines was 3.1 months, similar to a 2 MW onshore wind turbine based in Western Denmark, an area with very good wind resources (Ibid).

C. ENERGY TRANSITION

The modern, wind energy transition in Denmark is representative of a hybrid shift in which community activists, scientists and industry mobilized with government contributing closely through policy adaptation. In this transformative process, a wind industry emerged with entrepreneurial commitment that built on historical research and technology antecedents. The energy transformation occurred in a country of roughly 5.5 million people and an economy of about $165 billion (2000 prices, ppp, IEA, 2011a).

Denmark is a world leader in wind energy technology and wind power utilization. It is known as a center for top wind turbine and blade manufacturers (DWIA, 2011) and as of 2009, wind technology was the single largest export for a number of years (Maegaard, 2009). In comparison to other countries, Denmark is also known as the country with the highest wind penetration in its electricity mix for many years (Wiser et al, 2012); Interviews, 2011-2012). As of 2011, wind comprised 28% of total electricity (Energinet, 2012)[13]. At that time, 6,721 GWh of wind power was produced domestically, compared to negligible numbers in the 1970s.[14] Tied to this, Denmark is also a leader in wind power per capita at an estimated 1,212 kWh per person (Energinet, 2012, Maegaard, 2009; CIA, 2012).[15]

[13] Reported shares of total electricity derived from wind power for Denmark may differ slightly across sources, based on assumptions and definitions.

[14] Note: 1978 is the earliest year for which grid-connected electricity from wind power is reported by the DEA. However, anecdotal insights indicate that wind generation was negligible for the years 1970-1977.

[15] This is calculated based on an estimated population of 5,543,453 (CIA, 2012) and wind generation of 6,721 GWh (DEA, 2010).

Historical Background

Use of wind energy in electricity has deep roots in Danish history. Poul la Cour, the "Danish Thomas Edison" established a wind turbine test station at the Askov Folk High school in 1891, where he taught wind electricians and installed some of the world's first electricity-producing wind turbines (Ackermann and Soder, 2000; Gipe, 1995; Nissen, 2009; Redlinger et al, 2002).[16] A La Cour-based wind turbine design was commercialized around the time of WWI and by the end of the war, 120 Danish rural power stations utilized wind turbines with rated power of 20-35 kW, producing roughly 3% of Danish electricity (Meyer, 2011; Redlinger et al, 2002; Andersen, 2007).[17] This early experience with wind energy would not sustain in its share of the electricity market over the following few decades, but (like Poul la Cour's early research) would provide a cultural reference point.

Coal and oil increasingly dominated global and domestic energy use over the next few decades (Chapter 1, Figure D1, Interviews, 2011-2012); nonetheless, wind power research continued in Denmark, the United States, the United Kingdom and Germany, etc (Meyer, 1995; Jorgensen and Karnoe, 1991). During the interwar and WWII period,

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[16] Some students of La Cour's wind electrician course later built turbines for the F.L. Smidth company, during WWII (Krohn, 2001b; Krohn, 2002a). La Cour was also behind the founding of the world's first *Journal of Wind Electricity,* the Danish Wind Energy Company, and the Society for Wind Electricians in 1905 (Krohn, 2001b; Jorgensen and Karnoe, 1991).

[17] By 1918, roughly 3 MW of installed wind capacity was in place relative to the total Danish electricity capacity of 80 MW (Meyer, 1995). Around the same time, 30,000 windmill units were producing mechanical energy with a wind power equivalent of 150-200 MW (Meyer, 1995).

Danish companies F. L. Smidth and Lykkegaard Ltd. drew upon areas, like the emerging field of aerodynamics, to produce 30-70 kW windmills (Andersen, 2007; Gipe, 1995; Pedersen, 2010; Jorgensen and Karnoe, 1991).

In the post-war period, Danish energy consumption continued principally with fossil fuels, however Danish power utility engineer and former La Cour student Johannes Juul began an R&D program on wind utilization (Anderson, 2007). A key element of his research was a 200 kW turbine with a 24 meter rotor that he installed in Gedser, 90 miles south of Copenhagen (Andersen, 2007; Pedersen, 2010; Jorgensen and Karnoe, 1991). The turbine, known as the Gedser model, operated from 1959 to the 1967, when it was discontinued (Andersen, 2007). When Danish entrepreneurs mobilized in the 1970s, elements of the Gedser model would be revisited, [18] becoming the basis for the dominant design which still persists today (Krohn, 2002a; Sawin, 2001; Jorgensen and Karnoe, 1991; Meyer, 1995).[19]

[18] This 3-bladed, stall-regulated and upwind turbine was designed with a horizontal axis, automatic yaw system, fixed pitch, asynchronous motor, and pitchable blade tips to modulate overspeed (Pedersen, 2010; Jorgensen and Karnoe, 1991; Pedersen and Xinxin, 2012; Thorndahl, 2009; Energinet, 2009).

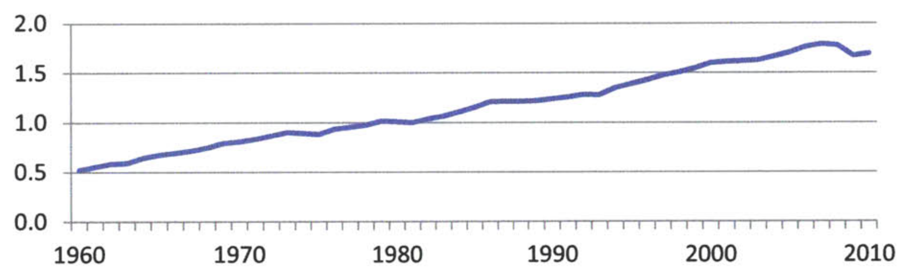
[19] The program supporting Juul's turbine was discontinued in 1962 when the Wind Commission concluded (based on a cost-effectiveness calculation of saved fuel rather than customer price) that the intermittency of produced power would reduce fuel consumption, but not the necessary capacity of conventional power plants (Jorgensen and Karnoe, 1991).

Denmark's Modern Wind Power Transition: 1970-the present

Like many countries in the early 1970s, Denmark was heavily reliant on oil imports and had little in the way of prepared contingencies for the oil crises. Around that time, 92% of the country's primary energy mix was fueled by oil, all of which was imported, primarily from the Middle East (Maegaard, 2009; Sawin, 2001).

Denmark had undergone rapid economic growth for more than a decade (Figure C1).

Figure C1: GDP *(Billion in constant US$, 2000)*



Source: WDI data, 2012.

Its traditional sources of income – namely, agriculture, small to medium-sized industrial craft-based enterprises, and shipbuilding - were being overtaken by rapid growth in construction, the chemical industry, electronics and pharmaceuticals, in addition to oil refineries and power stations (Jamison et al, 1990; Van Est, 1999). Oil had also been discovered by Denmark in the North Sea in 1966, and early development was underway.[20] In societal terms, youth revolts of the 1960s[21] gave way to some Danes questioning the rise of pollution, material growth and social welfare (Jamison et al, 1990; van Est, 1999, Interviews, 2011).[22]

Against the backdrop of the above developments, three periods of Danish wind energy development followed: 1970-1989, 1990-2001, and 2002 to the present (Figure C2).

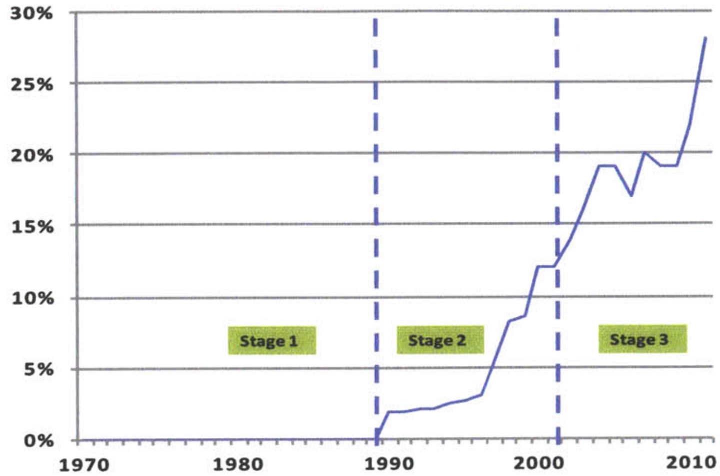
[20] Commercial extraction of oil in the North Sea dates back to the mid 1850s by Scotland and Germany (Glennie, 1998). North Sea natural gas was also found in the first half of the 20th century near Germany, England and the Netherlands (Ibid).

Denmark made its first discovery of North Sea oil in what become known as the Kraka field in 1966. Danish production began from the Dan field in 1972 (IEA, 2002). Contract renegotiations by the Danish government and oil and gas industry in 1980-1981 led to increased activity (Interview, 2012). Development followed in the Gorm, Skjold, Tyra and Rolf fields with gas production becoming operational in 1984 (IEA, 2011c).

[21] Danish protests appeared to focus on countering the increased centralization of society and environmental pollution (Interviews, 2011-2012; Jamison et al, 1990; Jorgensen and Karnoe, 1991).

[22] During the 1970s, collective awareness about energy and natural resource scarcity was informed by contemporary writing, including the Club of Rome's *Limits to Growth* (1972), Amory Lovins' *Soft Energy Paths* (1976/1977), and E.F. Schumacher's *Small is Beautiful* (1973) (Interviews, 2010-2012; Jorgensen and Karnoe, 1991).

Figure C2: Stages of Danish Wind Power Development
(Wind Power as a Share of Total Danish Electricity)



Source: DWIA, citing Energinet, 2012.

Danish wind technology developed based on technical insights from experimentation as well as use during an earlier era. Although essentially non-existent at the start of the 1970s, a wind energy industry would develop and professionalize. Somewhat differently from the consolidated roll-out of the Brazilian ethanol program, Danish wind policy would develop more incrementally over time.

Stage 1: Entrepreneurial Mobilization and New Market Formation (1970-1989)

Anyone looking at Denmark in 1970 would not have foreseen the wind energy transition about to occur. After Johannes Juuls's demonstration project with the Gedser turbine in the 1950s and 60s, there was little in the way of wind energy development until the first oil shock.

The oil crisis provided a wake-up call. Petroleum imports more than tripled in nominal currency terms for Denmark from 1972 to 1974, and increased by a factor of 7 between 1972 and 1980 (UN Comtrade, SITC REV 1, 2012). In Denmark's northern climate, energy consumers turned down their heat, insulated their homes, and began car-free Sundays (Energinet.dk, 2009). The electric utility ELSAM released a list of 10 potential sites for siting a nuclear power plant (Vasi, 2011). Around this time, the government also assigned responsibilities for energy policy matters to the Minister of Trade and Industry, announcing Denmark would accelerate nuclear development (OECD/NEA, 2007; Vasi, 2011).

A perceived urgency about Danish energy choices spurred inventors, scientists, environmentalists and communities into action to find practical alternatives for Danish society (Interviews, 2010-2012; Maegaard, 2009). Government also began to put policy measures in place to diversify the energy mix. A wind industry emerged and the power sector adapted.

Entrepreneurs and activists were some of the first to mobilize around the idea of scaling wind energy. Inventive citizens including farmers, blacksmiths, machinery manufacturers, and environmentalists drew upon technical skills, historical memory, and available components to begin tinkering with wind technology. One such entrepreneur was carpenter Christian Risiinger, who utilized interchangeable parts from other equipment to build a wind turbine with an asynchronous generator that he connected to the power grid. Accounts vary on whether his model was connected to the power grid with or without permission (Karnoe, 1990; Andersen and Drejer, 2008; citing Jensen, 2003; Grove-Nielsen undated; Energinet.dk, 2009). In any case, the turbine drew widespread attention and he later pioneered serial production of such wind turbines.

Environmental groups also committed to action. The Organization for Information about Nuclear Power (OOA) focused on stopping the use of nuclear power through public debate, information on alternatives, and the promotion decision-making related to nuclear power plants to occur in parliament rather than with from central authorities (Vasi, 2011).[23] The Organization for Renewable Energy (OVE) grew as a spin-off from OOA to focus on influencing energy-related policy and demonstrate the feasibility of RETs (Ibid).[24]

Inspired by the tenor of the times, dedicated amateurs at the Tvind school of Western Jutland set out to build the world's largest wind turbine (Tvind Internationale Skolcenter, undated; Karnoe, 1990). The volunteer Tvind crew partnered with interested scientists and others to construct a community turbine between 1975 and 1978 (Ibid; Grove-Nielsen, undated). As the project neared completion, an estimated 77,000 people visited the site over the period of months (Tvind Internatioinale Scolcenter, undated; Vasi, 2011). The resulting Tvind turbine, which operates at around 1MW and still runs today, provided local evidence that Danish ingenuity and ordinary communities could overcome oil import dependence (Interviews, 2010-2012; Grove-Nielsen, undated; Vasi, 2011).

[23] The Swedish Barseback nuclear power plant based 20 kilometers outside of Copenhagen provided an early point of opposition for the OOA. The Barseback plant, a boiling water nuclear plant, went into commercial operation in 1975.

[24] Its members participated in government committees and hearings on energy, published policy papers, established cooperative energy offices, and organized early knowledge-sharing meetings in the tradition of old Danish folk schools (Interviews, 2011-2012; Vasi, 2011, citing interviews with Preben Maegaard, Henrik Stresdal, Erik Grove-Nielsen). Folk Schools were the vision of N.F Grundtvig in the mid-1800s, designed to promote adult education, often without a degree granted.

In 1976, the government released its first national energy policy, *Danske Energipolitik* 1976. To insulate Denmark against energy supply crises, the plan prioritized fuel switching to nuclear and coal together with conservation (IEA, 1978; 2002; Meyer, 2004; Nielsen, K., 2005, citing Handelsministeriet, 1976).[25] The Danish Energy Agency was also formed to assist public authorities in overseeing the development, supply and use of energy (OECD/NEA, 2007; Sawin, 2001).

At this time, an alternative plan was also put forward by scientists from a number of Danish universities, outlining a path to energy self-sufficiency by leveraging renewable energy and efficiency (Blegaa et al, 1977). In addition to the Alternate Energy Plan produced in 1976, the Danish Academy of Technical Sciences (ATV) released two wind energy reports in 1975-1976, the first of which proposed a wind energy program for Denmark and the second outlined a five year action plan for wind energy (Meyer, 1995, citing Danish Academy 1975 and 1976, respectively). The first wind report concluded that 10% of Danish electricity could be derived from wind energy without altering the existing electricity system (Gipe, 1995, citing Pedersen, 1990).

[25] In conjunction with the Heat Plan which was also released in 1976, the Energy Plan highlighted: conservation targets to reduce the average energy growth of total primary energy; district heating to cover 20% of heating by 1985; natural gas to contribute an increased amount of the energy supply; imported coal to contribute 65% of electricity in 1995 relative to that of 35% in 1975; and finally nuclear energy for power production after 1990 (IEA, 1979). Production of North Sea gas could also begin in 1984, if a decision were made (Ibid). No decision on nuclear energy was expected before 1981, hinging on disposal solutions for waste management (Ibid).

Partly as a result of the early wind power studies and widespread interest, two government-sponsored energy R&D programs were initiated shortly thereafter. The *National Energy Program* supported, among other aims, research on large-scale turbines by Danish Technology University, electric utilities, and the government (Nielsen, K., 2005).[26] The *Development Program* was also formed to provide grants for projects, such as the establishment of the Nordic Folk Centre for Renewable Energy in Jutland, which has run since the early1980s (Ibid; see Drivers and Barriers).

In 1978, research on small-scale wind turbines was launched by the government with a test station at the Risoe Laboratory (Andersen, 1998).[27] The initial objectives for the station were to assess existing designs and assist in the design and development of evolving models (Ibid). In conjunction with this, a contact group and knowledge-sharing meetings were developed for wind turbine producers, the DEA, turbine owners, etc (Ibid, citing Handelministeriet, 1978).

With ongoing mobilization underway, two key industry organizations formed: the Danish Wind Power Owners Association (later Danish Wind Turbine Owners/DWTO or Danske Vindkraftvaereker) and the Danish Wind Mill Manufacturers Association (DWMA) (later

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[26] In conjunction with the National Energy Program, the original Gedser turbine of the 1950s and 60s was refurbished. Aided by computer design and aerodynamic blade theory, findings from the Gedser tests served as a basis for two, 630 kW test turbines: Nibe A (with stall regulation) and Nibe B (with pitch regulation) constructed for further testing (Nielsen, K., 2005, citing Handelsministreriets og elvaerkernes vindkraftprogram, 1981; and Karnoe, 1990).

[27] Ironically, Risoe was established in the 1950s to conduct research on nuclear energy, tied to work of physicist Niels Bohr (Andersen and Drujer, 2008).

the Danish Wind Industry Association/DWIA or Vindmolleindustrien). Both would serve in information-gathering, advocacy and negotiation capacities to safeguard the interests of their members in the decades ahead (Interviews; Karnoe, 1990, citing Vindkraftbogen, 1982). An early example of their activities included the DWTO partnering with Risoe to pressure wind turbine manufacturers to improve the technical reliability of early turbines with a more secure brake system (Karnoe, 1990). This brake system enhancement was a key, early development that distinguished Danish wind technology from others (Interviews, 2011-2012).

By the late 1970s, many of today's Danish wind experts demonstrated progress in their trade (Karnoe, 1990; Interviews, 2010-2012). A dozen small, Danish companies, including Vestas, Danregn (Bonus), and Nordtank were already producing and selling wind turbines (Grove-Nielsen, undated; Karnoe, 1990).

When the second oil crisis occurred in 1979, Denmark elevated energy oversight to the ministerial level, like a number of other countries (Meyer, 2004; IEA, 1980; Grubler, forthcoming). Heavy taxes were imposed on petroleum and electricity, and a policy of substituting coal for oil continued (IEA, 1980). During this period, North Sea natural gas and oil constituted some of the largest, indigenous sources of conventional energy that could be scaled in the energy mix for Denmark (see Appendix). However use of North

Sea gas required heavy investment and renegotiation of contracts (IEA, 1980; 1981; Interviews, 2011-2012).[28]

As economic pressures heightened, the Danish parliament passed legislation to stimulate employment and new energy technologies with the Energipakken. A key tenet of the legislation was an investment tax credit, paying up to 30% of capital costs for energy technologies, including wind power, solar power, biogas and heat pumps (IEA, 1984; Interviews, 2011). In order for wind turbine owners to claim the credit, they were required to use Risoe-certified turbines. This approach paired technology certification and financial support, creating a basis for industry, turbine owners and Risoe to work together (BTM, 1998), an important basis of support for the emerging wind power industry.[29]

Government mobilized in along different tracks. Parliament postponed a decision on whether to adopt nuclear power, pending findings on nuclear waste management studies (IEA, 1980, 1981; Vasi, 2011). The Center Left, Social Democrat-led government engaged in renegotiation of the oil and gas concession contract for North Sea exploration and development (Interviews, 2011-2012; Sawin, 2002). The Minister of

[28] A view of the time suggested that Denmark would be able to meet one third of its total primary energy needs by 1990 with stepped increases of oil and gas output in the North Sea (IEA, 1981).

[29] During the lifetime of the credit, approximately 2,567 turbines were supported (Nielsen, K., 2005, citing Energimiljoradet, 1998). The credit was reduced over time and phased out in 1989 after paying roughly $44 million (Meyer, 1995). A related estimate of this policy's cost in 1995$ places it at roughly $58 million (Sawin, 2001; see Appendix, Policy Table).

the Environment wrote to the local authorities, indicating the national government would support wind turbine installations by private individuals and encouraging local authorities to manage their permitting processes without undue delays (BTM, 1998). The Ministry also ordered utilities to provide grid access for small wind turbines and a fair deal on power generation payments (Ibid). [30]

To produce the new, wind turbine approval scheme, Riso scientists developed codes of practice and design standards based on an emerging understanding of manufacturer and turbine owner needs (Nielsen, K., 2005, citing Rasmussen and Jensen, 1999). They also fostered information channels with manufacturers, and focused research on problems that were discovered in the certification process (Interviews, 2011).

Risoe scientists also developed a ground-breaking wind atlas in 1981, using computational measures to estimate wind resource in complex terrain (Meyer, 1995 and 2004; Nielsen, K., 2005; Meyer, 1995, citing Petersen et al 1981). Manufacturers applied knowledge gained from the wind resource mapping in their production of small turbines (Nielsen, K., 2005). The Danish environmental authorities with the DEA in turn produced a national assessment which appraised the wind resource, the environmental

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[30] At the time, grid connections were arranged on an ad hoc basis and were not always readily carried out (Tranaes, 1997; Krohn 2002; Interviews, 2011-2012).

Grid connection rules were later established with a voluntary agreement in 1984 between utilities and wind power producers in which utilities agreed to pay 70-85% of the net customer price, excluding taxes and charges for wind power (Ibid; Meyer, 1995; Nielsen, K., 2005). The net price roughly equaled utility production plus distribution costs, which varied somewhat in relation to contemporary coal prices (Meyer, 1995). Rules for grid connection and reinforcement costs were also then included (BTM, 1998).

landscape, and planning conditions through 1986 for onshore and offshore wind sites. This information was made available to local planners and formed the basis for subsequent work by the Wind Siting Committee (Nielsen, K., 2005, citing Planstyrelsen, 1981-1986).

In policy terms, governmental support of wind development became more concrete in 1981, when the government introduced a generation subsidy for wind power on a per kWh basis (Sawin, 2001, citing Madsen, 2001). This subsidy, linked to energy taxes, would remain until it was replaced by a package of subsidies and taxes in 1992. Energy Plan 81 (Energiplan 81) was also released, maintaining the highly-debated nuclear energy dimension, but now also including socio-economic aims, like the decoupling of energy from economic growth and securing low cost community energy, together with environmental considerations (Danish Energy and Environmental Ministry, 1997; Nielsen, K., 2005). The plan incorporated a wind power production target of roughly 1.3 TWh to be attained by 1995 (Nielsen, K., 2005, citing Danish Ministry of Energy 1981) and emphasized continued conservation; extension of natural gas; production of combined heat and power (CHP) and acceleration of exploration in the North Seas (IEA, 1983). Similar to earlier events, the release of the government's energy plan was followed by the publishing of an alternative energy plan by independent energy experts from Danish universities (Meyer, 2005; Blegaa, 1977). Based on conservation potential models and new scenario methods, the alternative plan laid out a strategy without nuclear energy, promoting decentralized, combined heat and power (CHP), as well as

RETs, such as wind power, and conservation (Meyer, 2004, citing Hveplund et al, 1983).

For funding of research, development, and demonstration (RD&D), the government-sponsored Committee for Promoting Renewable Energy Systems became a central promoter of projects focused on wind power, solar power and biomass between 1982 and 1991 (Nielsen, K., 2005; Meyer 2004).[31] Under the leadership of solid state physicist Niels Meyer, projects included early analysis for offshore wind farm programs (Vasi, 2011; Meyer, 2004).

As the emerging Danish wind industry developed technology in a new domestic market, favorable policy and economic conditions in the United States presented an unusual and early export market to target (BTM, 1998; Interviews, 2011; DEA, 2011).[32] The

[31] Once running, the committee worked with a budget of roughly 4.6 million Euros per year or 30 million Euros for the total period (Meyer, 2004).

[32] The Public Utilities Regulatory Policies Act (PURPA) passed by the United States Congress in 1978, as part of the National Energy Act, promoted greater use of RETs. Under PURPA provisions, electric utilities were required to purchase power from qualifying facilities if the cost was less than what the utility would otherwise pay by producing the power or by purchasing it from an external source (avoided cost rate). Additional federal and state measures put investment tax credits in place which were applicable to wind generation. When federal and state tax credits were considered together, tax savings could equal 50-55% of the investment (Righter, 1996).

Furthermore, the California Public Utilities Commission decided upon high avoided costs to be paid for renewable energy-based generation in Standard Offer 4 contracts that were guaranteed for 10 years (Guey-Lee, 1998). In tandem with PURPA, this policy was an early precursor to feed-in tariffs.

Together with the above policies, favorable exchange rates also made it profitable for Americans to import Danish turbines (Karnoe, 1990).

investment boom in California wind power in the early 1980s motivated Danish wind turbine manufacturers to scale their businesses from batch production to mass production for export.

By 1985, 900 MW of installed wind capacity had been added in California from Danish and other sources (Guey-Lee, 1998). Of this market, Danish turbines grew from 5% to 50% of the market share between 1983 and 1985 (Karnoe, 1999, citing Stoddard, 1986). To meet the demands of the new market, many Danish wind technology companies quickly mastered business competencies in financing, insurance, and post-sales services (Karnoe, 1990).

Concurrent with growth in wind turbine manufacturing during the California boom years (1982-1986), wind technology gains were broadly in evidence. Advances in turbine size and performance could be seen with rated capacity increasing from 55-65 kW to 75-99 kW (Ibid). More specialized and less expensive components also appeared as suppliers accommodated the needs of the turbine producers (Ibid). One notable technical advance in 1984 was the emergence of a micro-processor control system that enhanced turbine performance and enabled centralized control of several hundred wind turbines (Ibid).

According to reports from the time, Danish turbines had the best technical performance record in the market (Karnoe, 1990, citing Stoddard, 1986; and Karnoe, 1990, citing California Energy Commission, 1988). During the boom period, one visiting, Danish scientist found that only half the wind turbines were operating on a windy day – Danish ones (Meyer, forthcoming, citing Meyer, 1983). For many, this was due to Risoe turbine standards and certification; informal, bottom-up learning; and performance feedback from turbine owners and that was reported in the Danish industry paper *Naturalig Energi* (Interviews, 2011-2012; Karnoe, 1990; Karnoe and Garud, 2003). One leading American wind engineer summarized the wind technology experience in 1986, highlighting technology uncertainty of aerodynamic loads and dynamic motions (Karnoe, 1990, citing Stoddard, 1986). He noted that the Danish models reduced design risk by: limiting aerodynamic load exposure, letting inertial forces overshadow the aerodynamic loads, and by preventing dynamic motions (Ibid).

When the California wind market collapsed around 1986, [33] Danish wind turbine manufacturers experienced an early crash. More than 20 bankruptcies occurred in the Danish wind sector and consolidation ensued (DEA 2011; BTM, 1998). Danish wind turbine manufacturers re-oriented production for the domestic market and returned to product development (Karnoe, 1990; BTM, 1998). By 1987, seven of the top ten wind turbine producers worldwide were Danish (Karnoe, 1990, citing Wind Power Monthly, 1988).

[33] American federal investment tax credits expired in 1985 and California ones expired shortly thereafter (Karnoe 1990). The 1986 collapse in oil prices and improved conditions for natural gas meant that avoided costs were less favorable for RETs after the 10 year Standard Offer contracts expired (Guey-Lee, 1998).

Danish owners of wind turbines up to this point consisted primarily of farmers, cooperatives, environmental activists, and other individuals (DWTO, 2012; Nielsen, K., 2005). This style of local development was facilitated by rules which limited turbine ownership to community residents living nearby (Interviews, 2011-2012; Hvelplund, 2011). Yet during the second half of the 1980s, another demographic group joined the ranks of wind turbine owners – utilities. Through its Ministry of Energy, the government made two deals with electric utilities (Elkraft, ELSAM and the Association of Electric Utilities): one in 1985 and a second in 1990, which obligated Elkraft and ELSAM to collectively install (without subsidies) at least 100 MW for each targeted time period (IEA, 1987; DEA, 2011; BTM, 1998; Karnoe, 1990; Tranaes, 1997).[34]

In the decade or so of wind development between the mid-1970s and mid-1980s, wind power had attracted a wide-ranging mix of supporters in Denmark. However, other groups in society, such as power companies and industrial actors, favored nuclear energy as the primary fuel of choice (Interviews, 2011-2012; Valsi, 2011). The Danish parliament in the mid-1970s voted favorably for the nuclear approach and, in the vernacular of energy systems, nuclear energy 'mapped' more closely with the centralized structure of the existing energy infrastructure. Yet, continued pressure from groups like Danish NGOs OOA, OVE and Friends of the Earth, general opposition by

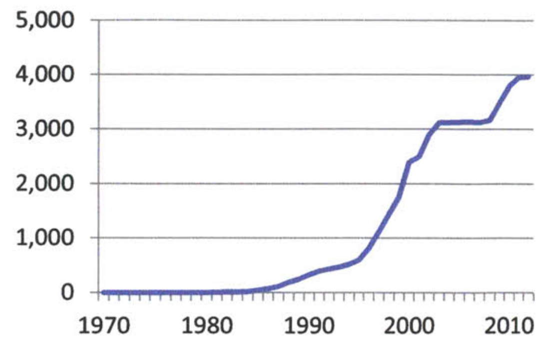
[34] Accounts on these deals vary. One view holds that the arrangement in 1985 was precipitated by utilities wanting to reclaim control of power generation inputs. The government agreed to set limits for independent power production, but also required utilities to cover part of increased wind production without the price guarantee available to independent power producers (Karnoe, 1990). Somewhat differently, a number of interviewees indicated that the utilities were reluctant participants at the time (Interviews, 2011-2012).

Danes to a Swedish nuclear plant sited nearby, the nuclear accident at Three Mile Island in 1979, and societal repositioning combined to overcome the forces in favor of nuclear energy. Parliament under a conservative government voted in 1985 for nuclear energy no longer to be considered an option in Denmark's energy planning (IEA; 1988; Meyer, 2004). The decision was reinforced a year later by the nuclear accident at Chernobyl.

Throughout the rest of the 1980s, utilities began to pursue plans with wind generation, but encountered delays due to siting issues (Karnoe, 1990) which would be addressed with new approaches to planning in the 1990s. Consideration began to shift to offshore wind platforms (IEA, 1988). In the summer of 1988, a government committee on sea-based wind published a report on potential siting locations for offshore wind (IEA, 1989). The report recommended that two offshore, wind projects be built to test economic, technical and environmental aspects (Sawin, 2001).

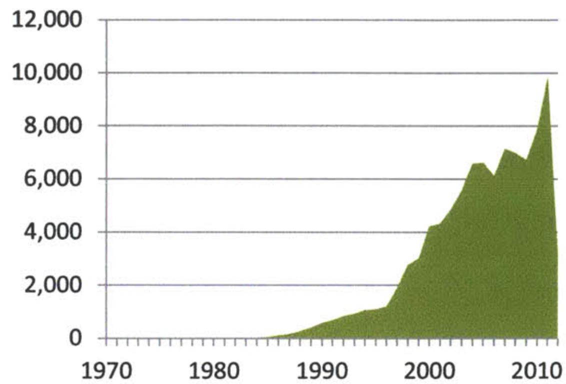
Overall, Stage 1 reflected the development of a wind industry in the establishment of wind power technology for a new market of activist users. It included early experimentation and technology development, key early-staged standard-setting, and policy development. For the years 1984-1989, exports represented 22% to 89% of total sales by Danish wind turbine manufacturers (see Industry section). Wind power as a share of total Danish electricity remained limited (Figure C2). However, wind generation and installed capacity for Denmark increased from negligible beginnings to 398 GWh and 247 MW, respectively (Figures C3 and C4).

Figure C3: Installed Wind Capacity (MW)



Source: 1970-1976, author's estimate; 1977-2012, DEA data, Wind Power Overview, as of March 2012.

Figure C4: Wind Power Production (GWh)



Source: 1970-1976, author's estimate; 1977-2012, DEA data, Wind Power Overview, as of March 2012.

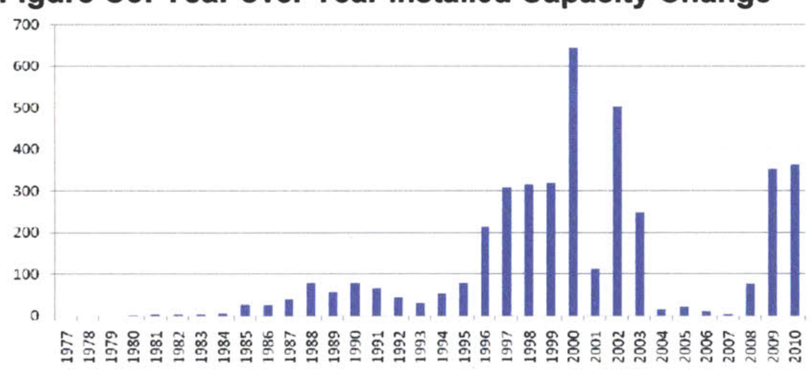
Stage 2: Adapting and Rapid Growth (1990-2001)

Broadly, the second stage of the Danish wind energy transition was marked by two robust energy plans focusing more on sustainable development and CO_2, an active Minister of Energy and the Environment, significant adaptation and learning with planning processes, and the early stages of liberalization in the electricity sector. However, the period began with a slow-down in domestic, wind turbine installations, and divisions between various industry and civil society groups. Government stepped in to mediate with mandates and incentives. Robust adoption of wind energy followed. The wind industry emerged from a period of adjustment and expanded back into international markets.

The release of a new energy plan, Energy 2000, provided an early basis for Stage 2 of Denmark's modern wind development. Produced at a time of increasing awareness about sustainable development and climate (Interviews, 2011-2012), the Plan contained extensive diagrams and calculations focused on CO_2 emissions reductions (Interview, 2012). It targeted four areas of change, namely energy savings; converting and enhancing supply with measures like CHP; increasing cleaner sources of energy; and additional R&D (IEA, 1992). Specific to wind power, it called for the installation of 1,300-1,500 MW by 2005 (Sawin, 2001). [35]

During the period of 1991-1993, domestic installations of wind turbines slowed, including planned projects by utilities (Figure C5; Sawin, 2001, citing AWEA,1995). Much of this was attributed to unresolved issues with planning; a 10% drop in electricity prices, affecting the price of power purchases; and a breakdown in negotiations between the wind associations and utilities on power purchases and grid costs (BTM, 1998; Interviews, 2011-2012).

Figure C5: Year over Year Installed Capacity Change



Source: DEA, 2011, using data from the DEA registry.

In response to rising concerns over the increased size and quantity of turbines, the national government established a siting committee which recommended there be

[35] The Energy 2000 Plan broadly focused on emissions reductions, while maintaining a reliable, efficient and economic supply of energy. Restructuring of the power sector was key to meeting reductions in CO_2, SO_2, and NO_x (IEA, 1993) by: increasing CHP to replace district heating and for use in industrial applications; shifting toward lower carbon fuels; demand side management; and development of wind power (IEA, 1994; 1995).

increased coordination of planning and siting (BTM, 1998; Sawin, 2001).[36] The national government released a national wind map with wind resource estimates to assist local authorities in planning (Krohn, 1999). This would later be extended with Risoe software for more detailed analysis in 1997 and a new Danish wind atlas in 1999 (ENS, 1998; Sawin, 2001).

Another mid-staged hurdle for Danish wind development was the impasse between the utilities and wind associations in renegotiating the voluntary power purchase prices and grid connection costs was. The Ministry of Energy and parliament took up the issue, setting a formal feed-in tariff in 1992 which maintained the previous voluntarily agreed price of 85% of the residential electricity rate.[37]

Specific to financing and economic support, a Conservative-led government of the early 1990s joined with the Danish turbine manufacturers and two Danish finance companies to establish the Danish Wind Turbine Guarantee (Sawin, 2001, citing IEA et al). This initiative was underwritten by the government and designed to support large projects using Danish wind turbines, by providing loan repayment guarantees with a 2.5 % premium added to the interest of the debt (Sawin, 2001). The government also

[36] The committee also identified an additional 1,000-2,800 MW of wind potential for harnessing (Godfretsen et al, 1992; Interviews 2011-2012).

[37] The cost of grid connection was also fixed so that turbine owners paid to connect to the low voltage, distribution grid, whereas utilities were required to pay for any strengthening of the high voltage, transmission lines (Nielsen, K., 2005; Vasi, 2011). This new arrangement was maintained until 2000, when (as a result of liberalization) a fixed nominal price was put in place (Vasi; 2011; IEAt, 2007).

replaced the performance-based RET subsidy of the 1980s with a set of support policies, including a revised RET subsidy (0.17 Dkk per kWh), a CO_2 tax, and an environmental subsidy-linked to the CO_2 tax (Ibid; Odgaard, 2000; Interviews, 2011).[38]

In what some might call a 'green turn,' the national government shifted from Conservative leadership of the 1980s to a Left-leaning, Social Democrat-led coalition. With it, the Ministries of Energy and the Environment were merged under one person, Svend Auken, who for nine years robustly promoted Denmark's deeper move toward green growth in the context of sustainable development (Interviews, 2011-2012). The national government also instituted new measures with local authorities, requiring that they develop plans for wind turbine siting (Krohn, 1997, citing ENS, 1994),[39] and identify suitable sites for zoning by 1995 (Krohn, 2002b; IEA, 1994; DEA, 2011). A study was also initiated to evaluate the potential for replacing/upgrading badly sited or inefficient turbines in conjunction with a 3-year repowering program that was instituted to replace such turbines (IEA, 1995; ENS, 1998; Sawin, 2001). From these measures, more closely synced planning between local and national authorities was established and has continued.

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[38] The European Commission, now more actively engaged in environmental and energy policy of its member-states, approved this set of wind support policies that would accompany a new rule on RET power purchases (Sawin, 2001, citing EC 1992, referenced by OTA).

[39] The passage of the 1994 Electricity Supply Act also stipulated that electricity utilities must use integrated resource planning in their management, which included least cost planning to account for conservation as well as development, including information sharing with the government and other utilities (IEA, 1999; Sawin, 2001).

As planning and economic policies were realigned, Danish wind development advanced with offshore wind. The government asked utilities ELSAM and Elkraft to build two offshore wind projects (Sawin, 2001), resulting in the launch of Vindeby and Tuno Knob wind farms in 1991 and 1995, respectively (Ibid).

Trends in private turbine ownership also began to shift by the mid-1990s from cooperatives to individual farmers due in part to laws opening new opportunities for the latter (IEA, 2004; see Innovation, and Drivers and Barriers sections). The ownership and residency rules of the mid-1980s were also incrementally relaxed and eventually abolished with liberalization only to be partly revived around 2008 to assure local ownership opportunities (DEA, 2012; Interviews 2011-2012).

A new energy plan was released in 1996, focusing on efficiency and RETs; maintaining a coal moratorium that had been put in place earlier (Maegaard, 2009); and tackling the transport sector for persistently growing CO_2 emissions (IEA, 1997). The Plan confirmed wind targets of 1,500 MW (12% of electricity consumption) for 2005 and set a new wind target of 5,500 MW from wind (40-50% of electricity) by 2030 (IEA, 2001).

In line with evolving policy, another deal was struck by the national government with utilities to add 200 MW of wind power by 2000 (IEA, 1998). Denmark became self-sufficient in energy on a net basis in 1997 (IEA, 2002a). New offshore planning rules were also put in place, establishing one-stop-shopping for regulatory approvals (DEA, 2012, 2008). The government instituted processes for offshore wind which involving an auction-based approach (i.e. tendering) in addition to an open door process, which allowed developers to initiate projects without prior bidding calls (IEA, 2001). Utilities worked with the Minister of Energy and Environment's Energy Authority and Environmental Protection Agency to map potential offshore wind sites which equated to 4,000 MW of immediate potential (IEA, 2004). Utilities also initiated preliminary proposals for projects (Krohn, 1997). Shortly thereafter, a requirement was placed on power companies to install an additional 750 MW of offshore wind before 2008 (Ibid; DEA, 2011).

More widely than the early 1980s, the Danish wind industry re-engaged in the international market. Countries, like Germany, Spain, India and China, instituted policies to adopt wind power (GWEC, 2011). With these new markets, Danish wind manufacturers often exported turbines at a level which exceeded domestic sales (see Industrial Development).

The influence of the European Community's supra-national authority was also evident with the European-wide movement to open the electricity market with liberalization (IEA, 1995, 1999, 2000).[40] In Denmark, the electricity market was deregulated by decision of the Danish Parliament with the Electricity Supply Act of 1999, designed to complement

[40] Liberalization and restructuring are processes that occurred in many regional power markets, like Denmark, France and Iceland. Liberalization opens the market to forces of supply and demand, reduces the level of government intervention and limits the barriers to market entry (Berg, 2005; Jamison et al, 2004). Restructuring entails the disaggregation of a vertically integrated company functions with the unbundling of services and centralized decision-making, whereby owners and operators of newly-configured companies become discrete entities (Ibid, see also Appendix).

EU guidance and Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 (Olsen and Skytte, 2002; Interviews, 2011).[41] As a test case for tighter regulations of state aid for RET energy, negotiations also occurred between the Danish government and the European Commission on Danish rates for funding wind generation (DEA, 2011).

The Electricity Supply Act (Law no 375, June, 2 1999) plus political agreements among parties formed the basis for opening competition in the Danish electricity market (IEA, 2002). With this arrangement, there would be a phased reduction of subsidies for wind power and restrictions on ownership of turbines abolished. There would also be a decrease in public investment, a CO_2 emission ceiling and renewable energy credits (RECs) introduced as a means to transition to a RET market (Maegaard, 2009; IEA, 2001). The expectation of these policy shifts led to an increase of wind turbine installations as the existing policy window came to a close in 1999-2000.

In technology terms, the size, performance, components and materials for wind turbines continued to evolve (see Innovations). An interesting technology anecdote lies in the actions of Danish wind manufacturer Bonus (owned as Siemens Wind, since 2005). Bonus attempted to leapfrog ahead of its peers with a larger turbine model and significantly improved MW yield (Andersen and Drejer, 2008, citing Andersen and Drejer, 2006). However, this leap did not fully materialize at the time. With the novel generation level that Bonus wanted to attain, new challenges would consequently follow

[41] Through the Danish Act, full competition was in place in 2003, enabling consumers to purchase electricity from suppliers of choice (Energinet, 2009).

for collaborating suppliers and sub-contractors within the Danish wind industry hub (Ibid). None of the collaborators wanted to assume the risk to support only one company, so Bonus postponed its generation-skipping design to wait for its competitors to catch up (Ibid). Apparently, learning, risk and industry progress were closely linked.

In terms of country-level energy development, Denmark's shift from its import dependence was well evident by 2000. The once-heavily reliant country was 142% self-sufficient on a net energy basis (IEA, 2002a). At the close of 2001, Denmark had the highest share of electricity generation from CHP in the world and one of the largest district heating systems (Ibid). The Danish energy intensity was below the IEA Europe average, neighboring countries (Sweden and Finland), and peer countries (Netherlands), due much to the use of CHP (Ibid).

More specific to policy and wind development, the EU approved Danish electricity reform except for regulations guaranteeing minimum prices for new wind turbine installations during liberalization transition. Price reductions from 0.60 Dkk/kWh to 0.43 Dkk/kWh were to occur in the near future, contingent on turbine age and accumulated production. Regulated limits on private ownership were withdrawn (IEA, 2001) and there was uncertainty about buy-back rates. Tax on wind income was largely the same as on other income, and most of the 205 municipalities had wind turbine plans prepared (IEA, 2001). The first, large offshore wind project (40 MW) was commissioned at Middlegrunden. Denmark also released Climate 21 in March 2000, assessing Danish climate policy to prepare for ratification of the Kyoto Protocol (IEA, 2001).

Over the course of the second stage of Danish wind development from 1990-2001, significant growth was evident. Exports rose from 1990 to 1999 alone by roughly a factor of 18 and represented 52-95% of Danish wind turbine manufacturers' sales (Sawin, 2001). Wind power as a share of total electricity rose from 2% to 12% (Figure C2). Wind generation and installed capacity grew roughly 8 fold to 4,312 GWh and 2,497 MW, respectively (Figures C3 and C4).

Stage 3: Domestic Stasis, Continued Export and Eventual Resumption of the Green Growth Strategy, 2002- the present

The 3rd stage of Danish wind development encompassed major flux tied to politics, RET policy, and the electricity market. Liberalization progressed as a new Right-wing government entered office in November 2001 and began a policy overhaul with a market-based orientation. RET support programs were eliminated and the Ministry of Energy and Environment was split. New wind installations slowed until a policy 'correction' in 2007.

The most recent decade of Danish wind energy development began with policy uncertainty of a postponed shift to green certificates in 2001- 2002 and a government that was less politically supportive of renewables (Interviews, 2011-2012).[42] The Venstre government came to power in 2001 and, with a right wing coalition, eliminated many of the RET support policies (Ibid). Transitional implementation issues of the green certificate policy also resulted in the introduction of a market premium (Meyer, 2004; IEA, 2005; Interviews, 2011-2012).

[42] The green certificate plan was in anticipation of an EU-wide shift from feed-in tariff-styled policy mechanisms, which did not materialize (Interviews, 2011-2012; Mendoca, et al, 2009).

With the market premium approach, RET generation was to be sold at market prices with an additional premium paid by electricity consumers (DEA, 2011). This premium, combined with repowering measures from 2000 and 2003,[43] became the cornerstone of economic support for the near-term. Project support hinged on the original year of grid connection, the onshore-offshore status of the project, and the turbine size (DEA, 2008, 2009, undated; see also Appendix). [44]

In 2002, the new conservative Danish government rescinded a previous executive directive to build 3 additional offshore wind farms (DEA, 2011).[45] With the exception of some repowering[46] and offshore development, domestic investment in wind projects ground to a halt between 2004 and 2007 (IEA, 2004; Maegaard, 2009; Interviews, 2011-2012).

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[43] Repowering replaces old turbines with more efficient ones.

[44] The current premium for new generation is approximately $0.05/KWh for the first 22,000 hours of full load for wind turbines connected to the grid as of February 19, 2009 (DEA, 2009 and DWTO, 2009). An additional $.01/kWh is paid during the production lifetime of a grid-approved turbine to compensate for the cost of balancing, etc. Private wind turbines under 25 kW that are connected from a residence, receive a fixed FIT of $.13/kWh (DEA, 2009).

Repowering includes additional coverage. Development and demonstration of new energy technologies is also supported by a fund which distributed approximately $126 million (750 million Dkk) in 2009 and $168 million (1 billion DKK) in 2010 and each year thereafter (DEA, 2012).

[45] This was partly reversed in 2004 by a political agreement with six coalition parties to install two offshore wind farms that are 200 MW each (DEA, 2011, Maegaard, 2009).

[46] The first repowering scheme ended with the replacement of 1,200 older, small turbines by 300 larger ones (IEA, 2004).

In conjunction with liberalization, the Risoe-based certification process was opened to international competition (IEA, 2004).[47] Other changes, like the appearance and growth of market actors, including balance responsible players, would allow wind power producers to collectively manage their power flows.

In the area of research and development, Risoe formed a consortium with DTU, Aalborg University, and the Danish Hydraulic Institute in 2002 (IEA, 2005, 2006b). A test station was also established for large, multi MW turbines at Hovsore (IEA, 2005). In 2006, the Megavind partnership was established to maintain Denmark as a globally leading hub in wind power.[48] Another major area of R&D is EU-backed Project Upwind which has the largest public private partnership for wind technology and focuses on studies related to very large MW turbines (IEA, 2007; Upwind, undated).[49]

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[47] Private enterprises could be authorized to perform approval services, certify, test and measure (Ibid). The approval scheme also underwent revision to an internationally accepted scheme with the International Electrotechnical Commission (IEC) and European Committee for Electrotechnical Standardization (CENELEC) standards (Ibid).

[48] Through concerted efforts by industry, academia and government, the partnership focuses on aims to "make offshore wind competitive with newly built coal-fired power, and in the process most likely achieve cost-competitiveness with all other new-built electricity generation, except for onshore wind (Megavind, 2010).

Its partners include: Vestas Wind Systems A/S, Siemens Wind Power A/S, DONG Energy, Grontmij I Carl Bro, The Technical University of Denmark, Riso DTU - National Laboratory for Sustainable Energy, Aalborg University, Energinet.dk (observer) and Danish Energy Agency (observer) (Megavind, 2010).

[49] Risoe leads as the coordinator of this 5 year project (Ibid; Webb, 2012). Based on modeling to compare theoretical designs with existing turbine technology, the group recently reported that a 20 MW turbine is feasible (Upwind, 2011).

By the mid-2000s, the Danish wind industry accounted for 70% of energy exports and roughly 40% of the global wind power market (DEA, 2005; Interviews, 2011-2012). Denmark also met its 2005 wind target in advance (Nielsen, K., 2005) and a second repowering scheme was launched (IEA, 2006a, 2006b). Danes paid roughly 0.2% of GDP for RET support (wind and other RETs) (IEA, 2006a). The DEA also estimated that the all-in costs of onshore wind turbines fell from about 10 Euro cents per kWh in the 1980s to 7.5 in the early 1990s and 4.9 in 2004 (Ibid). Global sales of Danish wind turbine manufacturers had increased from roughly 200 MW/year in the prior decade to 3,000+ MW/year (Ibid). Roughly, 25+% of consumed electricity and district heating was derived from RETs (Ibid).

Specific to oversight and institutional change, the energy ministerial functions were transferred to the Ministry of Transport and Energy (IEA, 2011a). In the electricity market, Energinet.dk, the Danish transmission system operator, was formed with liberalization and the merger of Eltra, Elkraft System, Elkraft Transmission, and Gastra (IEA, 2011a). It is an independent public enterprise owned by the State and represented by the Ministry of Climate, Energy and Building (Ibid). At the local level, Danish municipalities were consolidated in 2007, reduced from 271 to 98 (Milojminsteriet, 2012). In addition to the merger of Risoe with DTU, a shift in government also occurred in Fall 2011 toward a more pro-renewables agenda (Interviews, 2012).

The year 2007 and 2008 were major turning points for Danish wind. The former reflected an unusual low for Danish wind development in terms of installed capacity, as more wind turbines were decommissioned than installed (Maegaard, 2009). In a major turn-around from its earlier platform, the Government acknowledged that RETs were a priority and outlined a vision for Denmark without fossil fuels by 2050 (IEA, 2011a; DEA, 2011). The following year, a major political agreement was forged including: increased economic support for RET-based electricity with a cap on load years (DEA, 2011)[50] a new target of 20% renewables in total gross energy consumption; a new rule on local participation; backing for a new test station at Osterild; and a call for tenders on an offshore wind farm of 400 MW for 2012. To address the range of interests, the agreement also included additional measures like a loss of value scheme (DEA, 2011).

In the last several years of Stage 3, Danish companies held 90% of the accumulated, global offshore wind share (DWIA, 2011/2012). *Green Energy* was published by the independent Danish Commission on Climate Change Policy in 2010, offering 40 recommendations on how to convert the present Danish energy system to a more comprehensive green growth path (IEA, 2011a). A Left-leaning Social Democratic-led government returned to office in 2011. *Energy Strategy 2050* was released including policy instruments to transform Denmark into a low carbon society with a stable and affordable energy supply (IEA, 2011a). That same year, Vestas debuted a 7 MW offshore wind turbine (Webb, 2012). In March 2012, parliament passed a long-term

[50] For onshore pricing, see Market Premium above. Offshore wind pricing has been settled in recent years by auctions. The Horns Rev II wind farm (200 MW) has a fixed feed in tariff of 51.8 ore/kWh for 50,000 full load hours. Rodsand II (200 MW) has a fixed tariff of 62.9 ore/kWh for 50,000 full load hours. In 2012, the Anholt Offshore wind farm owned by DONG Energy is expected to go into operation with a feed-in-tariff of 105.1 ore/kWh for 20 TWh (DEA, 2012).

energy agreement, with 95% approval[51] setting a framework in place for energy and green development through 2020 with broader targets for 2050 (DWTO, 2012). The agreement centers on an ambitious green transition of energy savings, jobs and the harnessing of more wind, biogas, biomass, etc to convert all of Denmark's energy supply (power, transport and heating) to renewables by 2050.[52]

Overall, from 2002 to 2011, the wind share of Danish total electricity grew from 14% to 28% (Figure C1). Wind generation and installed capacity grew roughly 1.5-2 fold to 9,846 GWh and 3,952 MW, respectively (Figures C4 and C5). With decommissioning and repowering, there were 4,973 active wind turbines in Denmark as of the end of March 2012 (DEA, 2012).

Recap

In the four decades studied, Denmark has evidenced a clear shift in its energy status and strategy. While it began the period without a national energy policy or a ministerial level energy agency, it developed offshore oil and gas resources and shifted from the status of an oil and gas importer to a net exporter of both (IEA, 2002a, 2011c). Wind

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[51] This includes the current group in government plus the Liberal Party, Danish People's Party, the Unity List and Conservatives (DWTO, 2012).

[52] Some of the highlights for 2020 include: over 35% of total energy from RETs, nearly 50% of electricity form wind, and CO_2 emissions <34% of 1990 levels. Wind power for 2020 entails: 600 MW offshore wind turbines at Krieger's Flak and 400 MW at Horns Rev in 2020 with an additional 500 MW near-shore wind by 2020; strengthened planning for new wind with a total cap of 1,800 by 2020 (including decommissioning), etc (http://www.kemin.dk/Documents/Presse/2012/ Energiaftale/Faktaark%201%20-%20energiaftalen%20kort%20fortalt%20final.pdf)

energy rose from off-grid, negligible numbers to become a mainstay of the power sector, accompanied by the establishment of a new industry and market. Denmark rapidly converted electric power plants from oil to coal, and expanded the use of CHP and district heating systems (IEA 1982, 2004; Maegaard, 2009). In addition to wind power, Denmark developed RETs, including biomass, and biogas/waste, along with conservation and efficiency among its energy sources (IEA, 1988). The expansion of wind power and CHP/DH enabled the Danish power system to become much more decentralized.

D. INNOVATIONS and ADAPTATIONS

Innovations and adaptations in the Danish wind energy transition are described next for:

- Wind power technology - performance and size; components, materials and design; offshore technology;
- Cooperative ownership
- Advanced planning
- Grid and power market development

Wind Technology

Performance and size

Significant writing can be found on the stepped change of Danish turbine generations during the period of this study (Hansen and Andersen, 1999; DEA, 2009; Meyer, 2004). In terms of performance and size, early Danish turbines were often <10 kW on average and 40-70 meters in height, while they now range from roughly 2 to 5+ MW and stand at a height of up to 200 meters (BTM, 1998; Hvelplund 2011; IEA, 2005 and 2007). Table D1 shows the changes in turbine output by installation year. The period between 1995 and 1999 represents not only the largest addition, but a clear change in rated output. By 2004, turbines were producing about 100 times as much electricity as the 1st wind turbines in 1980 (IEA, 2005).

Table D1: Existing Turbines by Output and Installation Year

Timeframe	0-225 kW	226-499 kW	500-999 kW	1,000+ kW	Total
1978-84	91	1	0	0	92
1985-89	425	43	6	0	474
1990-94	616	169	65	0	850
1995-99	218	91	1687	73	2,069
2000-04	44	2	812	526	1,384
2005-09	33	0	26	150	209
Total	**1,427**	**306**	**2,596**	**749**	**5,078**

Source: DEA, 2009.

Components, Materials, and Design

Changes in the performance of Danish wind turbines are attributable not only to the above shifts in size, Danish wind turbine components, materials, and design have also evolved substantially. Specific to components, early Danish turbine models used off-the-shelf parts that were interchangeable with other industries, such as the automobile industry (Maegaard, 2009; Heymann, 1998; Pedersen, 2010). This substitutability allowed significant early testing without the added cost of producing dedicated components. Since that time, wind technology has become increasingly specialized in terms of equipment as well as the industries and services tied to logistics, installation and transport (EWETP, 2008; Pedersen and Xinxin, 2012; Heymann, 1998). In the 'old days', installation might have entailed a couple trucks and a crane. Today's turbines are the largest rotating structures in a built environment and at sea (EWETP, 2008). Crane designers now ask wind turbine producers about their expected size needs 1-2 years in advance. Moreover, today's cranes can now narrow belt tracks for travel on small roads, then widen for installation of a turbine – designed specifically for the wind industry (Ibid).

Another important innovation was the introduction of a more secure brake system in turbines of the late 1970s-early 1980s (Karnoe, 1990; Interviews 2011-2012). This adaptation enhanced the reliability of the early Danish models which likely factored in the appeal of the Danish model for export markets (Interviews, 2011-2012).

Material enhancements were also evident in the move toward stiffer and lighter carbon fiber blades from more conventional glass fiber and other materials. This advance, embraced by companies, like Vestas of Denmark (and Gamesa of Spain), means that turbines can have larger blades (i.e. wider swept space) with less robust turbine and tower components, thereby translating to higher energy output, efficiency and overall savings.[53] The Vestas V112 3MW model incorporated this feature for low to medium wind strength regions. This model is characterized by 179 foot blades with a blade width similar to its 144 foot blades, but the new model sweeps an area that is 55% larger with substantially greater energy output (Wood, 2012).[54]

[53] Carbon fiber material is more expensive but this is offset by cascading costs savings, such as that from adding 16 feet in blade length without weight gain.

[54] Currently carbon is typically used in the spar, a structural part of large blades (148+ ft). The increased stiffness and reduced density of carbon fiber allows a thinner blade

However, not all companies view carbon as the way forward, given supply concerns and higher prices currently for carbon. LM Wind Power (formerly LM Glasfiber), a globally top-ranked blade-manufacturer based in Kolding, Denmark is finding new ways to work with glass fiber. It recently installed 240 foot blades which were a composite of glass fiber and polyester on a 6MW turbine off shore in France.[55] The 240 foot blade weighs 20 metric tonnes, but employs 35-40% more attachment bolts into the same 11 foot blade root diameter as the competition's 202 foot blade model (Wood, 2012a). This allows the blade root to support blades that are up to 20% longer, without changing the root diameter (Ibid).

Offshore Technology

Denmark launched the world's first offshore wind farm in 1991 with its Vindeby demonstration project and has since completed the installation of 11 more projects (Table D2).

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profile with stiffer and lighter blades. However, more use of carbon is accompanied by new challenges since carbon requires perfect fiber alignment and must be cured perfectly (Wood, 2012a, citing Schoeflinger).

[55] LM Wind Power's approach, like Siemens Wind Power (formerly Bonus of Denmark) includes an enhanced manufacturing process with automation, studies of aerodynamic and load design, and more integrated designs of turbines and rotors (Wood, 2012b).

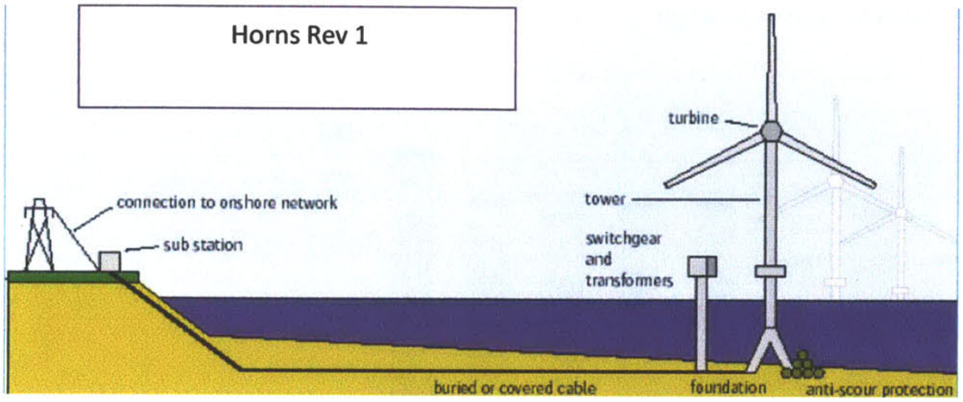
Table D2: Offshore Wind Farms

Vindeby (1991)	11 turbines, 5MW
Tuno Knob (1995)	10 turbines, 5 MW
Middlegrunden (2000)	20 turbines, 40 MW
Horns Rev I (2002)	80 turbines,160 MW
Ronland (2003)	8 turbines, 17 MW
Nysted (2003)	72 turbines, 165 MW
Samso (2003)	10 turbines, 23 MW
Fredrikshavn (2003)	3 turbines, 7 MW
Horns Rev II	91 turbines, 209 MW
Avedore Holme (2009/10)	3 turbines, 10-13 MW
Sprogo (2009)	7 turbines, 21 MW
Rodsand II (2010)	90 turbines, 207 MW
Anholt (2012) planned	400 MW
Fredrikshavn	6 demonstration mills

Source: DEA, 2012.

These 'marinized' versions of the onshore models must, among other technology changes, handle the robust conditions of the sea and corrosive effects of sea water. In the most basic configuration, they require the connection of the turbine to a foundation and use of a subsea cable to transmit the power supply to shore (Figure D1). The distinct character of the resource assessment, installation and support structure, water depths, irregular waves, aerodynamics, hydrodynamics, mooring, and control system, access and maintenance are a number of areas that also needed procedural and technological address for projects to advance (EWEA, 2009; Robinson and Musial, 2006).

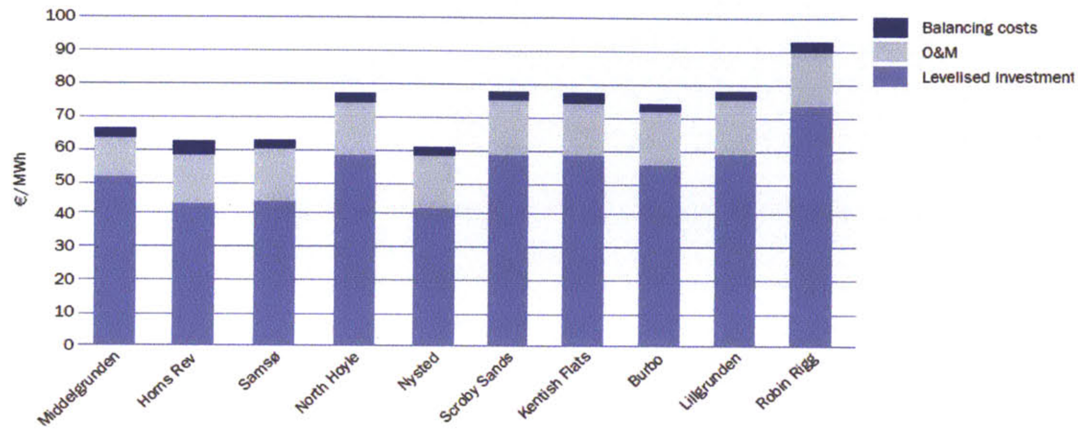
Figure D1: Typical Offshore Wind Farm Design



Source: Robinson and Musial, 2006, referencing Manwell.

As other regions adopt offshore wind power, data for cross comparisons is now becoming available. Figure D2 offers a highly simplified way to gauge Denmark's progress with offshore wind technology. It shows the calculated production costs for select wind farms in the United Kingdom, Sweden, Denmark - all of which have been installed since 2000. From this one finds that Danish projects, namely Middelgrunden, Horns Rev, Samoe and Nysted, have the lowest costs. Among projects based elsewhere, Burbo in the United Kingdom has the lowest production costs. This wind farm is owned and managed by DONG Energy, Denmark's partly state-owned energy company.

Figure D2: Calculated Production Costs for Select offshore Wind Farms, including Balancing Costs *(2006 prices)*



Source: EWEA, 2009, citing DTU Risoe.

Analytical Tools

Wind analysis and modeling tools related to resource assessment and forecasting have also advanced considerably over the past 30 years (EWEA, 2009; Interviews, 2011-2012) with contributions from actors, including Risoe and Energinet.

In the 1980s and 1990s, Risoe created a new atlas method which has been refined over time to produce more accurate analysis of wind resources. Risoe also uses numerical and mathematical models, based on aerodynamics, structural dynamics and control, to develop design improvements to enhance the maximum energy output from the wind under optimized loading conditions (Risoe, 2012; Interviews, 2011-2012).

Energinet has also played a role, particularly in the innovation of advanced forecast tools (Chandler, 2012). Forecasting is vital to system operation and day ahead/cross-border congestion management, to coordinate the commitment and economic dispatch of controllable power plants, to perform contingency analysis, and to assess the grid transfer capacity and the need for regulating power (Ibid). Energinet developed an operational planning system tool for integrating forecasts of wind and CHP into system planning up to 2 hours ahead of the time of operation (Chandler, 2012). This tool, *Drift Planlaegnings,* shows power flows between the Danish, German and Swedish systems. Currently, Energinet is working to shorten the time horizon for power flows to 5 minute increments (Ibid, citing Jones, 2011).

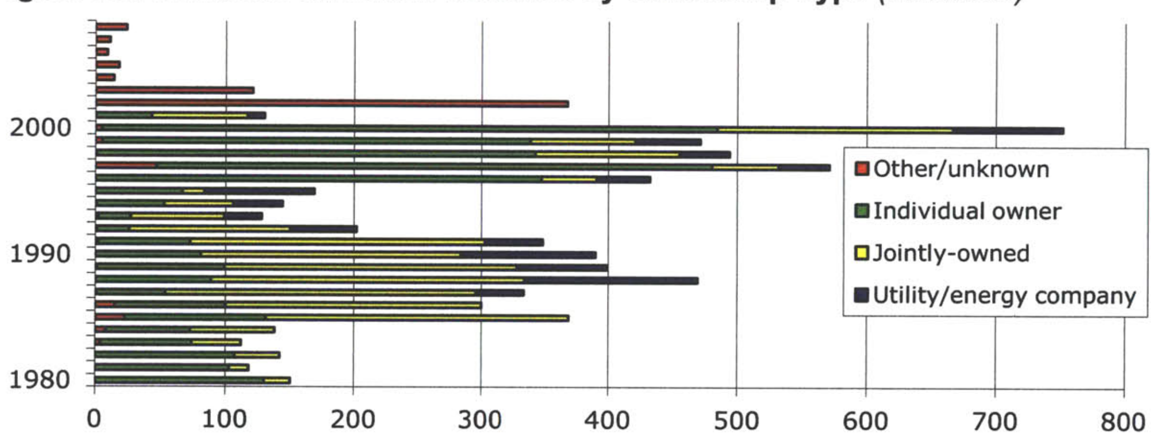
Cooperative Ownership

The application of cooperative ownership to turbine adoption is another adaptation worth underscoring. This often entailed autonomous associations of people who came together voluntarily to meet common social and/or economic aims through a jointly-owned and democratically-controlled enterprise (DWTO, 2009c). This type of collaboration has been used in Denmark in other areas since the late 1800s as a way to meet objectives, but had nearly disappeared by 1970, except for use with some electric utilities (Interview, 2012; DWTO, 2009c; Krohn, 1999, BTM, 1998).[56]

[56] 19th century Danish philosopher and teacher N.F.S. Grundtvig put forward ideas on education and local self-sufficiency for rural communities that fused with insights about cooperatives from the United Kingdom to then manifest in Danish cooperative approaches to agriculture (Mendonca et al, 2009, citing Anderson 2008; Tranaes, 1997). Among farmers, cooperatives were formed for dairies, slaughterhouses and purchasing associations (Ibid). With other groups, coops were used to secure electricity,

From the beginning of modern Danish wind development, cooperatives participated in its adoption. Figure D3 shows the role of coops in wind development, as early as 1980. Such a wind power cooperative was often comprised of a few hundred small and local investors owning a cluster of turbines (Nielsen, F., 2002). Legally, these groups established formal partnerships, since interest on loans was tax deductible for private individuals in a partnership (DWTO, 2009c). Jointly-owned turbines were often held by partnerships with joint and several liability, which reduced risk, as bylaws required that such turbines be insured (Ibid).

Figure D3: Numbers of Danish Turbines by Ownership Type *(Additions)*



Source: DWTO data, 2012.

While other kinds of owners mattered for wind power adoption, cooperatives played a clear role in the mid to late 1980s, after the export market dissipated in the California market and bankruptcies of Danish wind manufacturers ensued. Additions of installed wind capacity in the local market, particularly through cooperatives, sustained the

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insurance, credit on property loans, etc (Ibid; DWTO, 2009c; Tranaes, 1997; Mendonca et al, 2009).

Danish wind industry during that period (Figure D3 and Interview, 2012). The peak of turbine additions by cooperatives occurred in 1988 with 246 new units (DWTO, 2012). Political pressure from this constituency also factored in the maintaining of rules and support for wind turbines in the face of utility opposition (Interview, 2012).

According to the Danish Wind Turbine Owners Association, roughly 15% of Danish turbines today are owned by cooperatives (2009c). This constituency's engagement has been critical to knowledge accumulation and public acceptance, since community members plan and take responsibility for energy savings through these projects (DWTO, 2009c; Nielsen, F., 2002). Recent, well-known cooperative-based wind projects include ones linked to Middlegrunden and Samsoe Island (Box D1).

Adaptive and Advanced Policy and Planning

Policy and planning emerged as another key adaptation in Denmark's modern wind energy transition. While the other cases evidence changes in policy, the case of Denmark is distinctive for continuous, value-additive (with limited exceptions), and incremental adjustments in explicit policy and planning measures that encouraged wind development and with coherency and stability.

Interestingly, the Danish governments did not choose wind technology as 'the winner' but rather focused on setting policies in place which encouraged diversification. As needs evolved in terms of planning and siting, grid access, research and information, investment climates, and technical needs, the various Danish governments modified policies and planning measures in a manner which helped to foster a mature market and technology (see Appendix Policy Table, Table D3, and Political Support under Drivers). It is worth noting that policy manifested as broad and formal plans, individual polices, agreements, and more subtly as 'urging' by the government to persuade constituencies like utilities and local authorities to act.

Box D1: Key Danish Energy Projects Based on Cooperatives

Middlegrunden is an offshore wind farm that was built 3.5 km outside of Copenhagen in 2000. This 'largest offshore wind farm of its time' is 50% owned by 10,000 owners of the Middelgrunden Wind Turbine Cooperative and 50% owned by DONG Energy (Middelgrundens Vindmollelaug, undated). The 40 MW project has become one of the most well-known wind farms worldwide with its arc of turbines built along Denmark's historic, maritime protection zone and its educational updates on wind production.

Samsoe Island reflects another, Danish energy project based on cooperative engagement. In 1997, this island won a competition held by the Danish Minister of Energy and the Environment to become Denmark's 100% renewable energy island. Since then Samsoe Island has implemented a 10 year plan to transform its energy balance. Through onshore wind (cooperatively owned), sustainable district heating, and private distribution systems, among measures, the Island has become a net energy exporter (Samsoe Energy Academy, undated). One project within the Island energy system roll-out includes three 1 MW wind turbines near the village of Permilille, owned by local farmers and a wind turbine owners association with roughly 450 members. Together with eight other onshore turbines, a normal year's production is 25,300 MWh, roughly equal to the consumption of 6,500 households (DEA, 2009).

Table D3: Select Policy Tools

	1970s	1980s	1990s	2000s	2010s
Grid access/priority in dispatch for Wind	Grid access for wind turbines required for certified turbines in 1979		Priority (by Danish law and later by EU Directive and Danish practice)		
Economic support					
• **Investment**	Credit for 30% of capital investment decreases over time to 0% for Riso-certified turbines				
• **Performance-based**	Government paid subsidies 1981-1992; Encouraged power purchase agreements between utilities and turbine owners which lasted until early 90s		1992 FIT formalized, later converted to a market premium in the 2000s		
Knowledge-based tools	Risoe began setting standards for turbines and certification in the late 1970s; Risoe developed a wind atlas with new methodology in 1981 for use in wind resource assessments;			Certification privatized with liberalization	
	Various reports on resource and siting feasibility, technology performance				
Guaranteed markets		Government-utility deals		Auctions	
Planning and permitting	Ad hoc	Rules for residency and distance from turbine put in place mid 1980s	Local governments directed to identify zones for turbines by 1995; New rules in 1998 for offshore and offshore oversight	Residency requirements eliminated with liberalization 2008-2009 rules require that projects allow 20% local ownership	
Repowering			Various schemes for repowering upgrades		
R&D	Large and small-scale wind research; RET Committee funding for SME demonstration		Various projects with Risoe		
Additional industry strengthening measures			Danish Credit Guarantee formed; various DANIDA foreign aid activities		

Note: See Appendix for more policy tools and Timeline.

Specific to planning, a number of changes appear critical. First, Denmark experienced early 'growth pains' in the late 1980s, as turbines and projects increased in size

(Interviews, 2011-2012). The national government then created a wind planning committee which recommended more integrated evaluation of community, environmental, and other needs in turbine siting (Meyer, 2004; Nielsen, K., 2005; Interviews, 2011-2012).

The national government also directed local authorities to identify adequate wind sites within their municipal plans, providing this information to the national government (Krohn, citing Miljo–og Energiministerioet 1994; Meyer 2004; Interviews, 2011-2012). This measure enabled more strategic and integrated planning. By the late 1990s, a new planning 'architecture' began to be established, designating different institutional oversight tracks and processes for onshore and offshore wind. For offshore wind, a one-stop-shop process was implemented with the Danish Energy Agency (DEA, 2012). With it, project developers now work with the DEA to secure permits and the DEA, in turn, interfaces with other governmental bodies to address competing interests involved in implementation (Ibid). The scope of the DEA includes strategic environmental appraisals of the offshore regions and monitoring of environmental impacts as well as future locations for offshore wind projects (Ibid). While the character of offshore wind projects shifted from directly negotiated/imposed governmental-utility deals to competitive auctions, an 'open door' policy has also been maintained in which a developer can propose an unsolicited project.[57] In terms of onshore wind oversight, the local municipalities hold principal responsibility for projects (DEA, 2012). Guiding principles were put forward at the national level and local authorities interpret or

[57] Executive Order no. 815 of August 28, 2000; EU EIA directive 97/11/1997.

supplement at their level. Rules are now in place for height; distance from residences; sound; habitat; and nature considerations; as well as environmental assessment; cultural heritage sites; among considerations (Miljoministeriet Naturstyrelsen, 2012).

To assist with the local planning, the national government created a Wind Secretariat to advise local authorities and gather information (Ibid). A working group has also been established to address the future of wind power planning with representatives from the national government (Ministry of Environment, Climate and Energy), TSO Energinet.dk, DWIA, DWTO, and others (Ibid). These approaches to planning are now being promoted and adapted in other locations (IEA, 2011d and 2004; UK Renewables, 2012; Northern Territory of Australia, 2012).

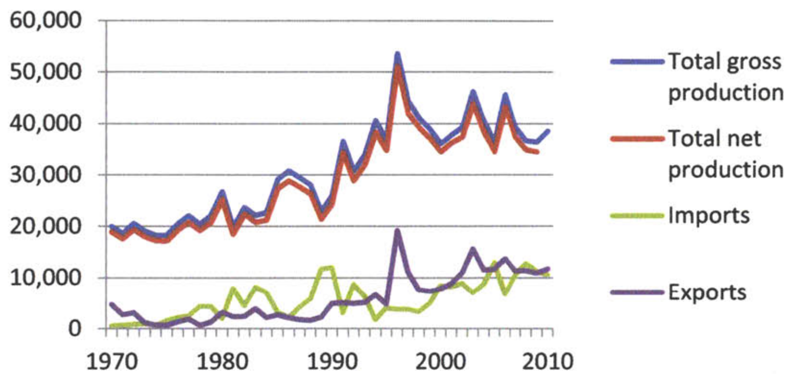
Power System and Market Developments

New kinds of flexibility in managing greater shares of wind power were gained through changes in infrastructure, institutions and practices in the power system and market.

Over the course of four decades, the Danish power systems and markets became more integrated in technical and market trading terms, as they grew. In the 1970s, Danish utilities ELKRAFT and ELSAM managed discrete grid transmission needs absent a connection between the Western and Eastern Denmark power systems. By 2005, transmission oversight of various regions was institutionally consolidated under TSO Energinet. The amount of gross electricity produced nearly doubled in Denmark from

20,024 to 38,568 GWh over this course of the period studied (IEA data, 2012; Figure D4).

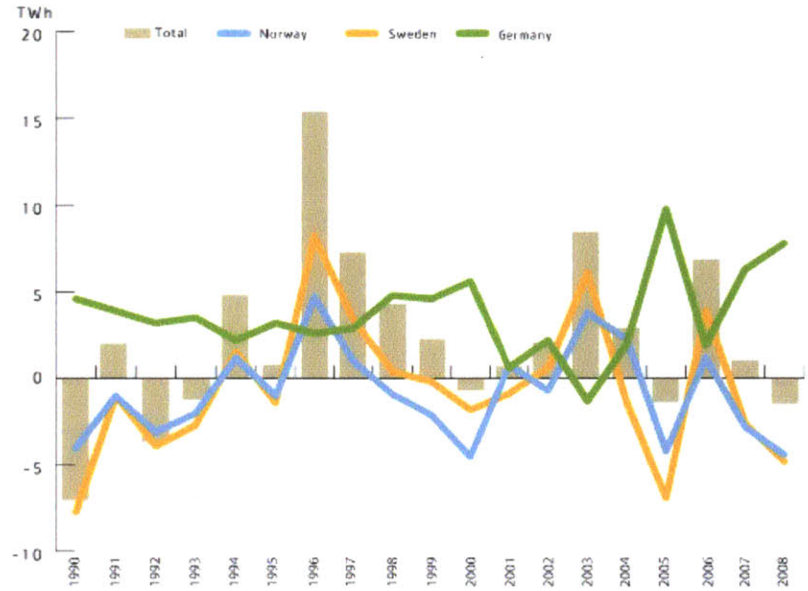
Figure D4: Danish Electricity, 1970-2010 *(GWh)*



Source: IEA data, 2012.

In conjunction with grid and other market changes to be discussed, net exports of electricity increased at least since 1990 (Figure D5).

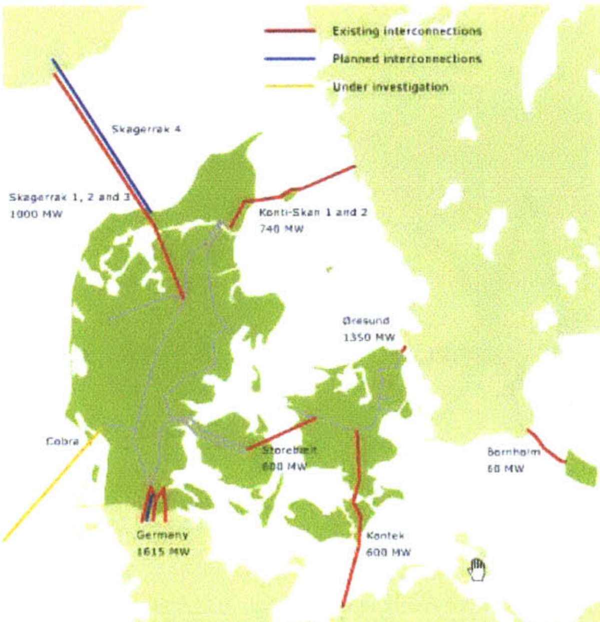
Figure D5: Net Exports of Electricity by Country (TWh)



Source: Eneriginet 2009c, referencing DEA data for 1990-2007 and Energinet 2008 data.

Specific to grid infrastructure, enhancements including interconnections to neighboring countries have been instrumental (Figure D6 and Appendix).

Figure D6: Danish High Voltage Interconnections



Source: Energinet, 2009c.

Technical expansion of the grid through interconnection enhancements enabled Denmark to participate in wider synchronous zones which integrate different power systems. Such zones operate at a synchronized frequency and enable pooling of generation, load, and reserves as well as partnered response during system disturbances. Denmark is part of the Nordic country synchronous zone, which includes the power systems of Finland, Norway, Sweden and Eastern Denmark and is interconnected via DC lines to Germany, Russia and Poland (EWEA, 2009). The Nordic system has a capacity approximating 90 GW with total primary reserves now at 1600 MW, comprised of 600 MW of operating reserve and 1,000 MW of disturbance reserve (EWEA, 2009). The interconnection capacity for Denmark, which caps the upper limit of electricity that may be imported or exported, equals roughly 75-85% of the Danish peak electricity demand (6,000 MWh/h) (Energinet, 2010). This high level of interconnection gives Denmark substantial system flexibility in smoothing wind flux. In a typical year, Denmark imports and exports about 30% of its total annual consumption (Energinet, 2009c). Additional interconnector links are being developed with Norway and the Netherlands.[58]

The gains of interconnection allowed not only greater latitude for market trading, but opportunity to technically smooth power flux with complementary generation. Connections in particular to Norway have provided Denmark with large, natural storage potential in the form of hydropower, as hydropower can be controlled more like fossil fuel or nuclear power plants. This capability eliminates the concern about responding to ramping conditions, for example.[59] Going further, it allows a regional 'cushioning effect' from hydropower which is highly favorable for movements of large-scale wind power. When this regional hydropower capacity is considered in conjunction with interconnection capacity, it is no surprise then that Denmark is exceptionally well-positioned for large-scale wind power from a technical standpoint.

[58] The Skagerrak 4 with Norway is a 600 MW high voltage DC (HVDC) connection due to begin operation in 2014 and a decision on the Cobra 700 MW HVDC link to the Netherlands is expected to be made by the end of 2014 (Chandler, 2012). Denmark and Germany are also planning a wind farm cluster, located at Kriegers Flak in the Baltic Sea that could be a step toward a regional offshore grid platform (Ibid).

[59] In 2009, Norway produced 132,778 GWh of hydropower-based electricity, roughly 96% of its total electricity (IEA data, 2012). By comparison, Denmark produced 36,364 GWh in that year of which 6,721 was from wind power (Ibid). This shows that Norway's entire power generation was 3 times that of Denmark's and 20 times that of Denmark's wind generation.

Still other technical gains with the grid system include greater wind power yields associated with benchmarking, performance monitoring, and greater focus on maintenance during low wind periods (Interview, 2012). Such changes in practices contributed in part to the rising share of wind power in Denmark's energy mix in the last decade, even as installed capacity remained flat.

The shift to competitive markets also factored in wind development (see Appendix, Power Markets-Vertically Integrated and Competitive Regimes). Like many other countries in the past two decades, Denmark underwent liberalization of its power sector from a monopolistic, vertically-integrated regime to a more competitive and geographically diffuse power exchange environment. With this institutional shift, power trading evolved from bilateral and often long- term contracts to a more diverse blend of transactions, enabling physical power and capacity assurances to be arranged in real time, intraday, day-ahead and other time spans.[60]

The power pool now used is regional in scope, involving multiple countries. Denmark participates in the Nordic power exchange with Sweden, Finland and Norway (Nord

[60] In Denmark, the shift from a vertically integrated regime to a competitive market began with the 1999 Danish Electricity Act which required the unbundling of generation, transmission ownership, grid operation, distribution and supply, as separate legal entities (IEA, 2003). In addition to the transmission system operation, local distribution also remained as a monopoly (Energinet, 2009). Organized wholesale market activity occurs in a mandatory pool model, based primarily upon: (1) Denmark's entry into the regional power exchange, (2) the Danish Competition Act, which produced the Danish Energy Regulatory Authority and (3) TSO Energinet.dk's market framework rules for electricity suppliers and balance-responsible market players (Energinet, 2007).

Pool, 2009).[61] This power pool allows for disposal of power transfers through implicit auctions, typically including spot and hourly trading; financial market activity, like derivatives and long-term contracts; and other forms of over-the-counter and bilateral trading (Ibid). With this pool, the scope of coverage and range of options extends well beyond that which was readily available in the pre-liberalized period.

Select Changes Relevant to Large-Scale Wind Power

Tied to the liberalization of the power sector, wind power integration appears to have benefited from gains of scale in larger competitive markets; options for complex maneuverability and flexibility with market and network options, mediated by price. Wind generation now trades in the power exchanges and often drives the overall market prices, since it is unencumbered by fuel costs. The natural outcome of this dynamic is beneficial in the short-run to end-users, since wind generation bids have an overall lowering effect on average marginal prices reflected in a pool, while addressing externalities.[62] In the long-run (at equilibrium), prices will need to rise to attract new investment in the required technologies. Subsequent to liberalization, market refinements continue, as with shorter gate closures for different trading markets. This

[61] The Nord Pool Spot market, where roughly 70% of consumed electricity was traded in 2008, is owned by TSOs from Denmark, Sweden, Finland and Norway (Energinet, 2009c). The 2008 turnover in its day-ahead auction market Elspot was 298 TWh (Ibid). By comparison, Denmark's observed power consumption that year was 34 TWh (IEA data, 2012).

[62] In an effort to send truer price signals, the Nord Pool adopted negative pricing in late 2009. With this mechanism, a negative price reflects unplanned or unnecessary surplus power supplied to the system (Nord Pool, 2009).

adaptation is conducive to wind integration, since the forecast accuracy of wind power increases as the time of delivery approaches.[63]

The substantial increase of combined heat and power (CHP) within Denmark over the past few decades favorably benefitted wind development by providing another means for the grid operator to smooth flux from wind generation (Maegaard, 2009; Interviews, 2011-2012). .[64] The combined effect of increasing CHP and wind power shifted Denmark's power system from a centralized to a decentralized one (Figure D7).

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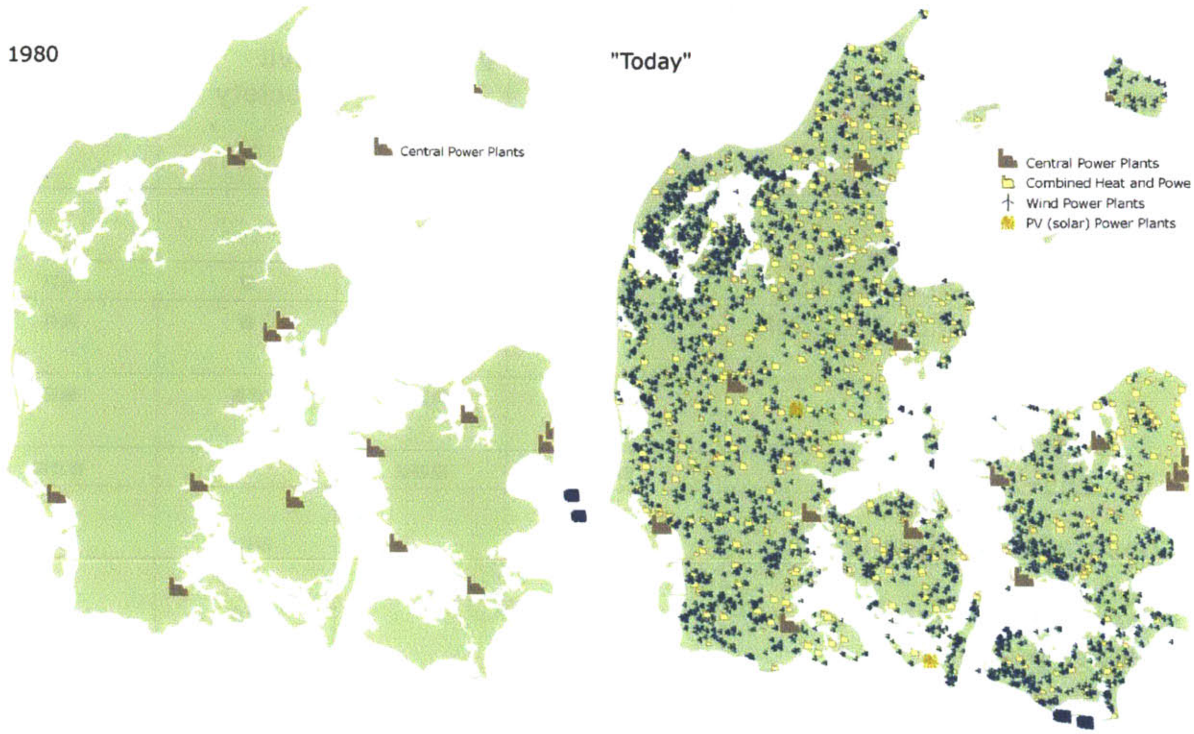
[63] Financial risk/penalties are assigned if scheduled power is not delivered, so shorter gate closures will enable wind power producers to more effectively report anticipated deliveries.

[64] Basically, CHP plants now employ electric boilers to generate heat and can compete in the power markets for downward regulation (Energinet, 2009c). By transforming wind energy into heat, this approach has CHP technically functioning like a battery which is charged when the TSO has surplus energy (Ibid).

Redlinger et al also point to increased use of biomass in the energy system, as providing enhanced operational flexibility (2002).

Figure D7: Shift in Danish Power Plants, 1980 and Today



Source: Communications with Energinet, 2012.

Sectoral Contributions

The strength of sectoral contributions in the above innovations and adaptations is laid out in Table D3 with some weighting. As with other cases in this study, estimated weighting is indicated by the number of squares per category and derived from the interview feedback, case analysis and historical reporting.

Table D3: Sectoral Contributions to Innovation/Adaptations

Innovation/Adaptation	National Government	Industry	Civil Society	Other (Academia, NGOs, etc)
Wind Power Technology				
• Performance and Size	■■	■■■	■	■■
• Components, Materials, and Design	■■	■■■	■	■■
• Offshore Wind Technology	■■	■■■	■■	■■
• Analytical Tools	■■	■■■		■■■
Cooperative Ownership	■		■■■	■
Advanced planning and adaptive policies	■■■		■■	■■
Grid and power market development	■■■	■■■		■■

**Note: Energinet is state-owned TSO with some independent latitude, so it falls under Industry and National Government. Risoe lab has had varying relationships over time, depending on funding and institutional change, so is grouped with National Government and Other. The DWTO, because of its composition and various mission activities, falls under Civil Society, Industry and Other. Local governments and the EU authorities are both classed with Other.*

From this summary table, patterns and differences in sectoral contributions can be discerned. Government, for example, is involved in all areas, generally because of rule-setting or funding. Industry, as expected, has major role in technology and grid/market developments. Civil society and those in the Other category, namely NGOs, labs and the EU, are involved in nearly all major developments as well. From a broad standpoint, this variability of contribution suggests that more decentralized problem-solving occurred.

E. KEY DRIVERS and BARRIERS

Major determinants of Danish wind energy development included the following:

Drivers:

- Desire for reduced oil imports/self-sufficiency/Balance of payment savings
- Significant and early local ownership
- Long-term political support for green energy
- Active and highly professionalized NGOs, scientists, and other individuals
- Local entrepreneurship - Tech savvy and tinkering nature with open source learning and pragmatism

Reduction of Oil Import Dependence - Improvement of the Balance of Payments-Foreign Exchange Savings - National Energy Security/Self-sufficiency

The intertwined goals of energy self-sufficiency and a strengthened trade balance through reductions in petroleum imports combined to be a force for change in the Danish wind transition. At the time of the first oil shock, Denmark depended on petroleum imports for 87% of its total final energy consumption (IEA data, 2012).[65] The import costs rose in nominal terms from $0.41 billion to an early peak of $3.71 billion in 1980 (Figure E1). Related to this, the cost of petroleum as a share of total import costs increased from 10% in 1973 to an early peak of 19% in 1980 and 1981 (Figure E2).

[65] Total final energy consumption differs from the share of the total primary energy mix mentioned in Section C.

Figure E1: Import Costs of Petroleum for Denmark (Billion, nominal $)

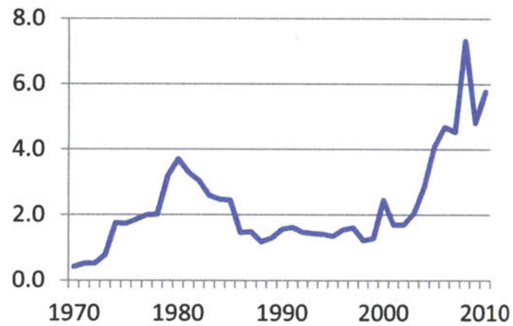
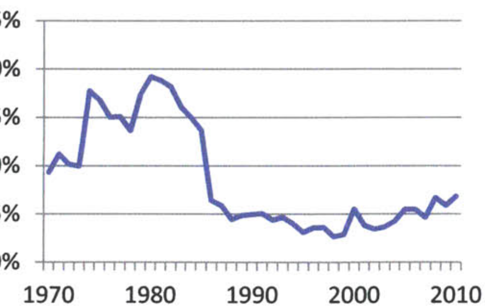


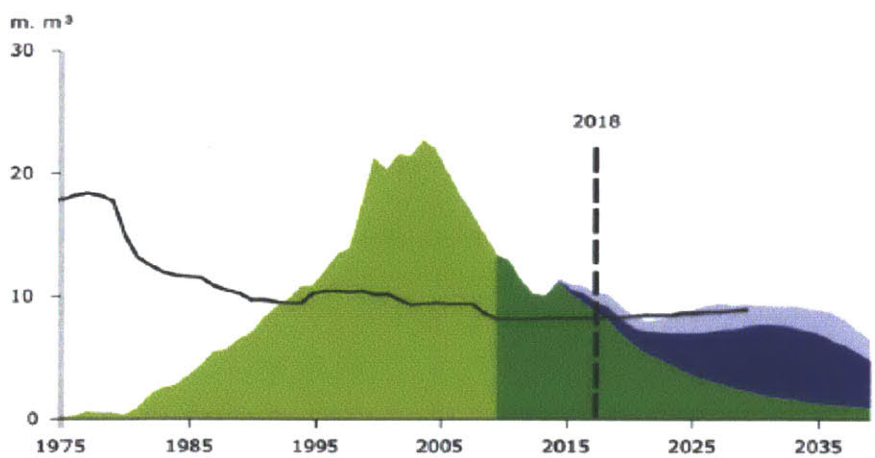
Figure E2: Petroleum as a Share of Total Import Costs



Source: UN Comtrade data, SITC REV 1, Petroleum and Petroleum Products, 2012.

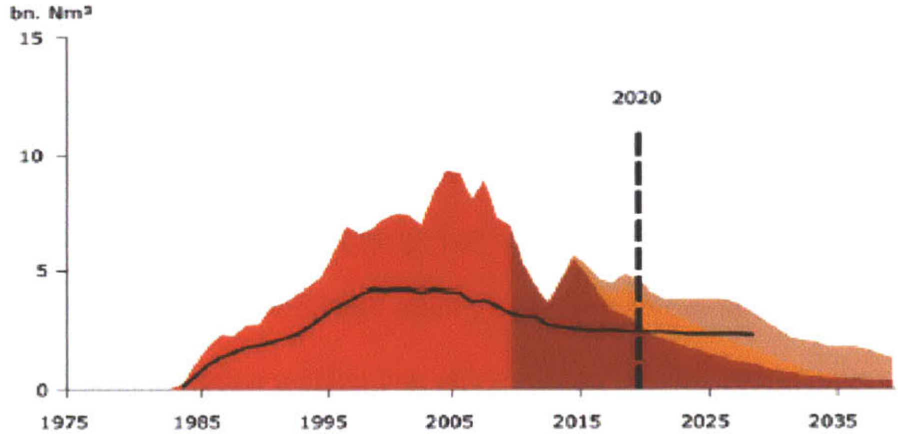
When considering alternatives to oil imports, knowledge of some oil and gas reserves in the North Sea existed (see Appendix), however Denmark was still in a very early stage of oil and gas exploration and development (Interviews, 2011-20912, Figures E3 and E4).

Figure E3: Crude Oil Production and Potential Production for Denmark



Source: IEA, 2011c, citing DEA. Light green: Production, Dark green: Expected production profile, Black line: Consumption, Light blue: Exploration resources, Dark blue: Technological resources.

Figure E4: Natural Gas Production and Potential Production for Denmark



Source: IEA, 2011c, citing DEA. Light red: Production, Dark red: Expected production profile, Black line: Consumption, Neutral pink: Exploration resources, Orange: Technological resources.

Local Engagement

Danish wind development would not be what it is today without the local engagement of individuals, like Danish farmers, and of cooperatives (discussed more fully under Innovation). As Figure D3 showed, such groups led the way in early adoption of wind in Denmark, providing an early market and source of feedback. Utilities did not participate as owners until around 1987.

What generally appeared to attract individuals and cooperatives as early owners of wind turbines were environmental concerns, philosophical interests in decentralization, a pragmatic penchant for providing one's own energy, and the opportunity to profit from the sale of wind power to the grid (Interviews, 2011-2012; Vasi, 2011). In the period from the mid 1980s through to liberalization, residency requirements protected local ownership opportunities and limited absentee ownership of turbines by external developers. Limits also existed on the amount of ownership any one investor could have in a cooperative (Ibid). As of 2002, more than 80% of the 6,300 wind turbines operating at the time were owned by wind energy coops or individual farmers (Krohn 2002a). This translated to roughly 150,000 families participating in wind energy production (Maegaard, 2009). With liberalization, repowering/decommissioning of smaller turbines, and the increasing size of turbines/projects (requiring larger financing more suited to developers and large-scale energy companies), there has been growth in other models of ownership, including public-private partnerships and utility-owned, nonetheless cooperatives and local ownership continue (Krohn, 2002b). As of 2008, rules currently oblige wind project developers to offer shares for local owners, so the trend in coop ownership may continue (DEA, 2012). Ownership approaches could also more fully shift to a 21st century form of cooperative in which Danish pensions invest in the wind turbine industry and project ownership (Interview, 2012).

Long-term Political Support for Green Development

Danish political parties and their general position on energy and the environment have provided an instrumental base to Denmark's wind power transition. Denmark had 20 parliamentary coalitions in the period from 1970 which included 10 prime ministers (Statsministeriet, undated). During this period, wind power, CHP/efficiencies, conservation and RETs in general received what many would characterize as long-term support (Interviews, 2010-2012; see Appendix Table A1).[66] This is based on a political

[66] In Denmark, politics are based on consensus. Within the multi-party parliamentary framework, no political party has held absolute power since the early 20th century and only four governments have held majorities since 1945. With such conditions, passage of legislation is typically predicated upon negotiation and compromise among parties.

balance attained with a green majority in parliament and many years of Social Democratic-led governments (Interviews, 2010-2012; Mendonca et al, 2009). Even during the 1980s, when Conservatives grew in strength, support was provided to wind power, based on its progress and potential associated with exports, jobs and industry, among other factors (Interviews, 2011-2012).[67]

An anomaly to this long-term support was evident in the last decade when an absolute Right-wing majority assumed power in 2001 (Interviews, 2010-2012). While shaped by the issue of immigration, the government also viewed energy and the environment through a very different lens. For the next few years, the address of energy was separated from that of the environment, policies shifted to market-based options, and RET programs were significantly reduced (Interviews, 20120-2012; Meyer, 2004).

As of 2011, Social Democrats once again lead a Center Left government. Robust and sustainable energy planning is now the focus, including wind power as an important component (Interviews, 2012).

[67] Danish political spectrum can be distilled into four categories - Left, Center Left, Center Right and Right - with the left-leaning groups typically favoring RETs and right-leaning groups favoring free markets (Karnoe and Buchorn, 2008; Interviews, 2011-2012). For the period of this study, the Center Left Social Democrats regularly partnered with the Center Left Social Liberals to support RETs. The more leftist end of the spectrum consisted of even stronger proponents of RETs. This cluster of all Left-leaning actors provided stability to Danish energy policy from 1977 to 1991, despite the absence of a formal Green Party (Karnoe and Buchorn, 2008). By contrast, Right-leaning Liberals, Conservatives and the Danish People's Party (Folke Party) positions ranged from those who were moderately to strongly opposed to or skeptical of RETs and government support within the energy sector (Ibid; Interviews, 2011-2012).

Activist Scientists/Experts and Highly Specialized NGOs

While the Innovation section of this study covers sectoral contributions, a number of key actors are highlighted here, as agents change (Interviews, 2011-2012). In terms of NGOs, the OVE and OOA were singled out as instrumental environmental NGOs which elevated the public discourse on renewable energy pathways as an alternative to nuclear energy (Ibid). Their specialized engagement, analysis and advocacy of energy options, effectively brought pressure to bear on the political process, so that nuclear energy was ultimately renounced by Parliament in 1985 (Vasi, 2011).

Another activist group was (and is) the Nordic Folke Center for Renewable Energy (NFCRE), based in Thy, North Jutland. Established by former head of OVE Preban Maegaard in 1983, the Center continues today. Dubbed an "energy evangelist" by one interviewee, the NFCRE is known for its demonstration of RET projects, training and information dissemination for the manufacture, industrial innovation and implementation of renewable energy technologies and energy savings (NFCRE, 2012). As international debates continue to be waged over positions on technology transfer (South Centre and Center for International Environmental Law, 2008), the NFCRE actively trains and launches projects in partnership with NGOs, companies, and governmental authorities from Europe, Asia, North and South American and Africa (NFCRE, 2012; Vasi, 2011).

Often working from within or in conjunction with the NGOs were activist experts from various labs, schools and industry centers based in Denmark. Such activists provided early engineering guidance for the Tvind school turbine which remains a symbol of

Danish ingenuity. Experts also guided wind studies in the mid-1970s with the ATV committee (Meyer forthcoming, citing Lykkegaard et al, 1975 and Hvelplund et al, 1976). They worked in the 1980s and early 1990s through the Steering Committee for the Promotion of Renewables to fund small to medium-sized enterprises interested in RETs and demonstration projects (Meyer, forthcoming 2012, citing Beuse et al, 2000 and Jørgensen at al, 1985). Such groups, which included leaders like DTU's Niels Meyer, were instrumental in producing 'counter expert reporting' for national energy plans and for shaping some early-staged demonstration of RET projects.

Local Entrepreneurship and Open Learning

A final driver, mentioned prominently in interviews as well as the literature, was local entrepreneurship and open learning. Here, Danish wind development was fundamentally characterized by bottom-up, trial and error style learning in which local entrepreneurs (often practical and tech savvy blacksmiths, mechanics, other individuals) tinkered with small-scale turbine design and implementation (Karnoe and Garud, 2003; Kamp et al, 2004; Vasi, 2011; Interviews, 2011-2012). This 'bricolage' approach to technology development, as Garud and Karnoe described it, occurred in an environment of open learning and with mode of accessible communication in meetings, journals, and demonstration projects (Heymann, 1998; Nielsen, K., 2005).

Barriers

- Grid connection
- Periods of uncertainty related to planning or policy change
- Niche resistance from various groups
- Stepwise learning of the industry

Grid Connection

In terms of barriers, limits associated with grid connection were mostly evident in Stage 1. This challenge drew attention from groups, like the DWTO, since power sales by independent power producers could not have broad application without grid connection (Interviews, 2011-2012).

Periods of Uncertainty Related to Planning or Policy Change

The most prominent barrier to wind energy adoption for the study was uncertainty related to planning or policy change at two junctures: the early 1990s and the period from 2001 to 2009. The issue in the earlier period was tied to increases in turbine size and proliferation, necessitating revised planning that would more fully involve both the local and national authorities. This was corrected once a siting study and local zoning assessment were completed, with rules and processes then put in place to clarify suitable steps and locations. The second period of uncertainty was associated with liberalization and the entry of market-oriented government in 2001 that did not favor RETs. During this time, wind installations came to a standstill with the exception of repowering and completion of utility deals.

Niche Resistance from Various Groups (See Social acceptance, below)

Step-wise Learning

Unlike the break-through style of technology development adopted by the United States and Germany that initially centered on large-scale turbines, Denmark generally adopted a more incremental approach of scaling from smaller models with trial and error learning in a close network of users, developers and certifiers (Garud and Karnoe, 2003; Heymann, 1998; Interviews, 2011-2012). This approach provided strong feedback loops and, by many accounts, enhanced industry and technology development as well as societal acceptance (Interviews, 2011-2012), yet it also, served as a brake on radical departures. When manufacturer Bonus attempted to disruptively advance in the area of turbine model size and yield in the 1990s, it found that its network of suppliers and sub-contractors within the Danish wind industry hub were not willing to assume added risks associated with the support of a unique design (Andersen and Drejer, 2008, citing Andersen and Drejer, 2006). Bonus decision-makers then chose to wait for the industry to catch up (Ibid).

F. CLASSIFYING CHANGE

To categorize the source and direction of the Danish wind energy transition, the early stage began as bottom-up-led with civil society and a nascent industry's mobilization. Governmental contributions began to quickly factor, making the overall stage highly hybridized. In Stage 2, very robust activity began after some realignment. Government, industry and civil society contributed during this stage, carrying the hybridized momentum forward. Stage 3 reflected an unusual shift with government pulling out of almost all wind energy development until the latter part of the decade. A stasis was evident with more or less no growth in wind turbine installations, other than from previously committed utility projects and repowering. Industry actors, specifically utilities, the new TSO Energinet.dk and wind turbine manufacturers sustained some momentum. Specific to manufacturers, this entailed sales in international markets. For the utilities and grid operator, progress was evident in managing a continually increasing share of total electricity derived from wind, as well as partnering on grid integration and harmonization with regional counterparts. In the very last part of Stage 3, a new government re-entered the circle of contributors, making the more recent years again hybridized. Fundamentally, Stage 3 was bottom-up-led. Overall, the Danish wind energy trajectory is a hybrid model with significant bottom-up orientation.

For the period since 1970, all forms of governmental intervention were evident. In the first stage of conversion, the government incentivized with the investment credit, induced with the certification process and R&D, and informed by sharing national assessment findings. Stage 2 entailed direct deployment with the implementation of guaranteed markets in government-utility deals. Inducement and informing were evident when the national government required local authorities to identify suitable locations for turbine siting. Wind power adoption was also incentivized by instituting a feed-in tariff in lieu of the stymied voluntary agreement between utilities and wind power producers.

Finally, Stage 3 entailed direct deployment/inducement with auction-based wind farms being installed. Incentivization was evident with the adoption of the market-based premium and repowering support.

It is worth underscoring, here, that the Danish government supported a diversified energy strategy, particularly after moving away from nuclear energy. Society had demonstrated a strong interest in wind technology and other options.

As for displacing traditional fuels with wind energy: Stage 1 was negligible; Stage 2 and 3 were both quite robust, with Stage 2 rising from 2% to 12% and Stage 3 from 14% to 28% (Figure C3). If the pace of change is gauged instead with installed wind capacity: Stage 1 was similarly negligible, rising roughly 13 MW/year on average; Stage 2 was the most robust, increasing on average 197 MW/year; and Stage 3 was mixed with growth at the beginning and end with a stasis in between, represented by a rise on average of 118 MW/year.

Specific to technology change, the wind turbines and wind assessment tools evidenced mostly continuous, incremental advances. For wind turbines technology, clear changes in size, performance, materials and design maintained a continuous technology transition trajectory over the course of the four decades studied. Two forms of discontinuous development were evident with the emergence of offshore wind technology and the shift in the power sector from a centralized to a decentralized/distributed orientation. Specific to wind analysis tools, such as those for resource assessments, tools appear to have advanced discontinuously with the development of the wind atlas approach in 1981, but subsequently evolved in a more continuous and incremental manner.

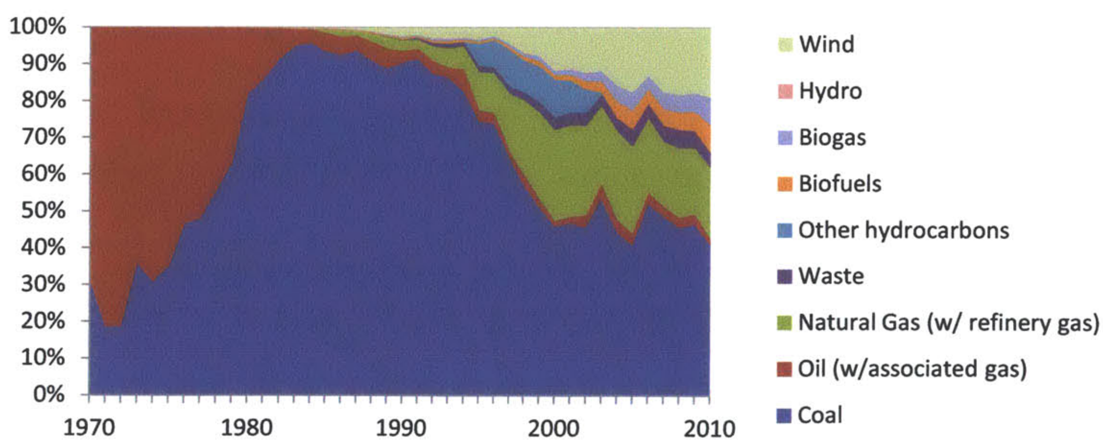
G. CHANGE INDICATORS

Indicators are considered for the Danish wind transition in terms of energy mix, costs, societal acceptance, and industrial development. Additional indicators may be found in the appendix.

Energy mix/balance

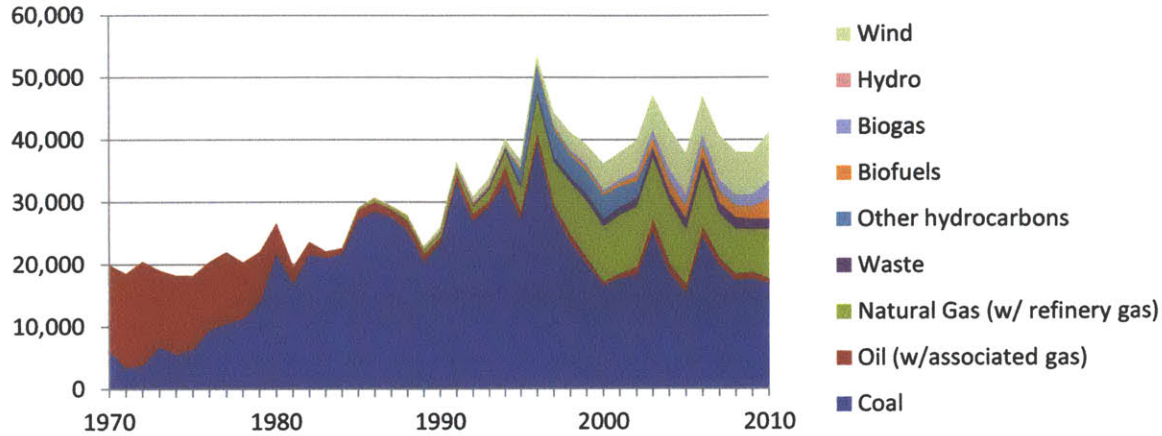
Specific to the energy mix, the share of electricity derived from wind power shifted from 0% to 28% between 1970 and 2011 – equaling roughly 0.7% per year on average. This conversion is shown in relative and absolute terms in Figures G1 and G2.

Figure G1: Fuels Used in Electricity Production *(Relative Shares)*



Source: IEA data, 2012.

Figure G2: Fuels used in Electricity Production *(GWh)*



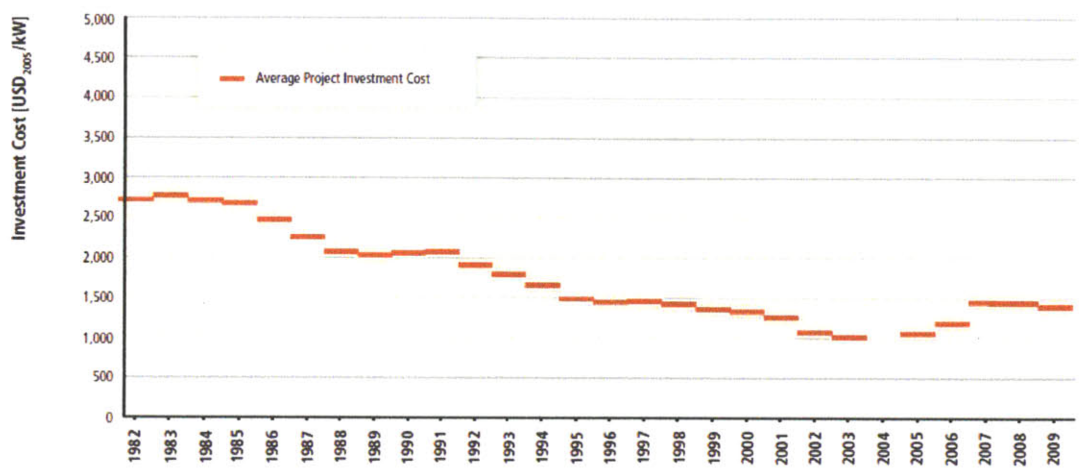
Source: IEA data, 2012.

Costs and Economics

Broadly speaking, the costs associated with Danish wind power and the economics of its industry have improved markedly since the 1970s. By some accounts wind power is competitive in areas with good resource and in relation to CHP (DWIA, 2012), however it is not fully competitive (Interviews, 2011-2012).

Specific to Danish investment costs, Figure G3 shows an overall improvement in the average costs of project investment per kW declining by roughly 44% from roughly $2,700 to less than $1,500/kW for Danish projects in 2009 (Wiser et al, 2012; Nielsen et al, 2010).

Figure G3: Change in Investment Costs



Source: Wiser, et al, 2012, referencing, Nielsen et al, 2010.

In a recent study of investment costs associated with wind power in Denmark, Germany, the United States and the United Kingdom during the period 1986-2000, Danish cost trends were found to be the lowest throughout the period with an exception around 1997 (Soderholm and Sundquist, 2007). Turning next to prices paid to wind power producers (including support), Denmark was fairly stable in a range of roughly 8 and 12 cents per kWh ($1998), which for the majority of the period reflected the middle of the rate bands for the four countries (Ibid).[68]

Another way to consider specific wind energy costs is in terms of their competitiveness. Currently, costs are roughly 0.35 to 0.40 DKK to produce a kWh of wind power with a new turbine in Denmark (Note: This accounts for the wind regime and size of the turbine) (Interview, 2012; IEA, 2011a). By comparison, the retail or market price earned

[68] Periods tested included Denmark (1986-1999); Germany (1990-1999); Spain (1990-1999), and the UK (1991-2000) (Soderholm and Sundquist, 2007).

by turbine owners averaged about 0.33 Dkk in 2011 with flux of 15-20% across years (Interview, 2012). Here, a market premium bridges the gap with an additional 0.22 Dkk for the first 22,000 full load hours (Ibid). The DWIA offers a slightly different view, indicating that wind power in good locations is currently competitive on a price per production basis with new CHP (DWIA, 2012), but is not competitive with other options, like combined cycle natural gas. While differences exists in this area, what can be said is that wind power costs have improved substantially, but are not yet competitive on a broad basis, absent support.

Turning next to learning curve costs for the period from 1981 to 2000, another study, evaluated different kinds of Danish wind energy curves: the price of wind turbines (Euro/kW) vs. cumulative capacity produced (MW); specific production costs (Euro/kW) vs. cumulative capacity produced; and levelized production costs vs. cumulative capacity produced (MW) (Neij et al, 2004). For each, an improvement was evident. Progress ratios showed that after the first doubling of production, (1) the prices of turbines, (2) production costs and (3) levelized costs declined respectively to 92%, 86%, and 83% of their original numbers (Ibid).

Looking next at the economic support during the core stages of scale-up, estimates for the period 1970 to 2000 indicate that $709 million ($1995) was spent for R&D and subsidies in Denmark versus $1,924 by Germany and $3,000+ by the United States for the same period (Figures G4 and G5; Sawin, 2001). Given the complex and often non-transparent nature of the funding processes, the data must be considered to be rough and not necessarily including all elements. In the case of Denmark, for instance, the estimate does not factor for revenue loss associated with tax depreciation deductions; long term loan repayment guarantees, where relevant; and export assistance (Ibid).

Figure G4: Economic Support ($1995)

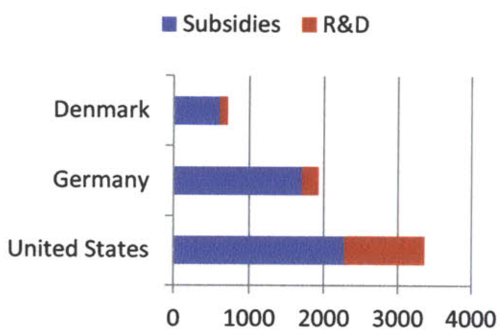
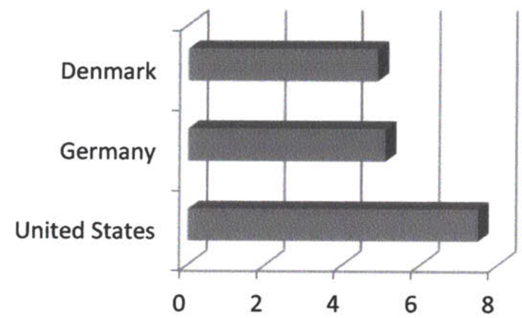


Figure G5: Economic Support per Unit of Power Generation (cents $1995/kWh)



Source: Adapted from Sawin 2001. Note estimates are rough and do not necessarily include all policy elements.

Over the last decade, changes associated with the shift in economic support to a Public Service Obligation (PSO)/market premium imply that costs are substantially reduced and spread across electricity users, rather than tax payers. Figure G6 shows the PSO essentially for clean energy through 2004 with individual technologies broken out separately thereafter (DEA, 2011b, referencing Statistics Denmark). Focusing strictly on 2005-2010, where wind technology is clearly noted, one can see that the economic support ranged from <1 to <2 billion Dkk. In 2010, it was 1.1 billion Dkk or roughly $190 million to meet roughly 22% of the Danish electricity supply (Ibid; Energinet, 2011). In those years, wind power and CHP appeared to vary in terms of their status of being the technology which received the larger share of PSO-related economic support relative to other technologies. If one then looks at Figure G7 for revenue from energy taxes, the 15 billion Dkk earned through CO_2, Sulfur, and Electricity taxes far exceeds the support costs of wind power.

Figure G6: Expenses for Public Service Obligations Related to Electricity
(billion Dkk current prices)

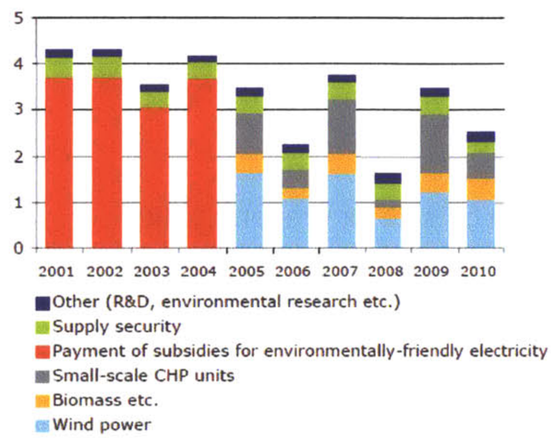
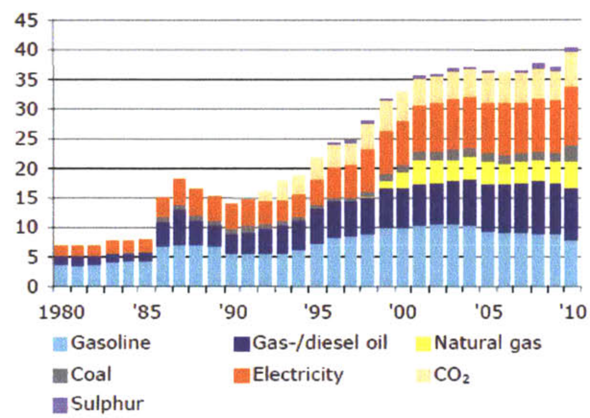


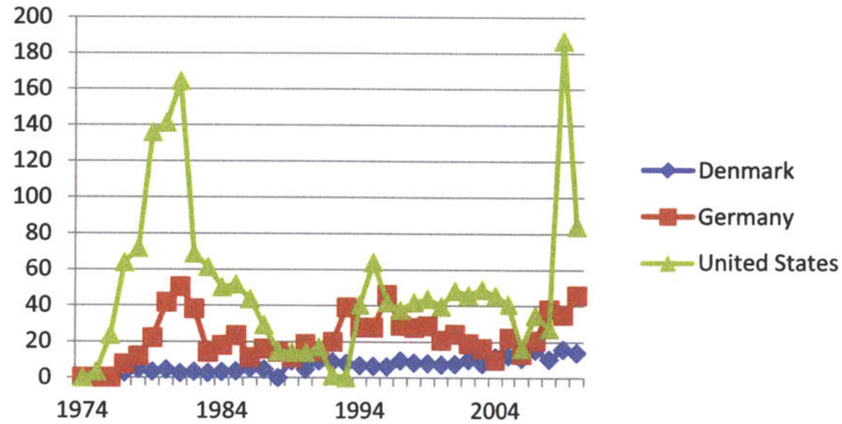
Figure G7: Revenue from Energy, CO_2, and Sulfur Taxes (billion Dkk, current prices)



Source: DEA, 2011a, referencing Statistics Denmark.

Another way to compare wind economics is to examiner energy RD&D spending on wind technology for Denmark, Germany, and the United States from 1974 to 2010. Here, Denmark spent substantially less in absolute terms (Figure G8). It was during this period that the Danish Gedser-based model became the dominant design and the Danish wind industry emerged as an international leader in wind turbine manufacturing (Righter, 1996; Sawin, 2001; Nielsen, K., 2005, citing Heymann).

Figure G8: Total RD&D Expenditure on Wind Technology ($ 2010 prices, ppp)



Source: IEA data, 2012.

Turning to the question, who paid? The answer must be split for pre- and post-liberalization. In the pre-liberalization period, utilities, electricity consumers and tax payers paid for economic support plus research and development. Now, costs appear to be more fully paid by electricity consumers with some continued coverage by tax payers for ongoing R&D.

Societal Acceptance

Discussion of social acceptance in the Danish case is multi-faceted.

In terms of supporters, engaged groups included environmentalists, farmers, inventors, individuals in favor of decentralized living and/or Danish energy independence, scientists/academics, politicians, families, schools, and communities. Those who resisted wind power development encompassed some utilities (early), nuclear energy supporters, some residents opposed to specific projects, tax payers who questioned profits of wind power producers, and the Danske Folke party in the last decade.

Position of the Utilities

Utilities have a complicated and mixed history in this case. They were mentioned as resisting wind development and in favor of nuclear development, particularly in the early years, yet they were engaged from the beginning with wind R&D from the standpoint of financing and researching (Krohn, 1999; Traneas, 1997; Interviews, 2011-2012; Sawin, 2011; Nielsen, K., 2005). After rules for grid connection and Risoe standards were put in place by the government in 1979, indications showed that not all utilities were supportive of connecting wind turbines to the grid (Interviews, 2010-2011; Tranaes, 1997). Nonetheless, an agreement between the utilities and wind associations was reached in 1984 for power purchase and grid connections. In the 1990s, the government stepped in, formally setting rules, when negotiations for a new agreement reached an impasse.

With regard to offshore wind, utilities often now lead the development in this area, albeit with strong early pressure from government (required deals) and academics (reports showing the feasibility of offshore wind). Fundamentally, utilities learned how to manage large-scale wind on the grid and with offshore dynamics.

Some say that the Danish utilities eventually ‘came around’ on wind power, when realizing that this form of energy was a fairly cost competitive way to meet environmental and regulatory aims (Krohn, 1999; Interviews, 2011-2012). Importantly, knowledge accumulation by utilities by the late 1990s enabled them to install wind capacity at lower costs than elsewhere in Europe (Krohn, 1999, citing ELTRA, 1998).[69]

In today's more liberalized environment these same actors are now putting large-scale wind management skills to use in other markets – either in international development (foreign aid) efforts or in business activities (Interviews, 2011-2012). Partly privatized DONG Energy, for instance, has made green growth and clean energy priorities to be principal dimensions of its business strategy, working internationally from this position (Interviews, 2011; DONG, 2012).

It is worth highlighting that utilities prior to liberalization were generally not-for-profit. They also typically had a consumer-based or municipality-based form of ownership. This feature may have lessened opposition to wind power, particularly if local residents wanted wind power. If these companies were to lose market share to independent power producers like local wind cooperatives, the situation might have been palatable, since the utilities were generally accountable to local residents, rather than market analysts and remote shareholders.

[69] Soren Krohn, former head of the Danish Wind Turbine Manufacturing Association, notes that power companies urged the government to leave wind development to them (rather than independent power producers) (1999). Going further, he suggests that the eagerness of utilities to purse offshore wind projects in the late 1990s is evident in their early applications for planning permission before a government order was issued (Ibid).

Pro-nuclear Supporters

Before Parliament voted to eliminate nuclear power from Danish energy planning, pro-nuclear supporters were often at odds with wind energy enthusiasts and others supporting 'soft energy' options of efficiency, conservation, and RETs.[70] The regular production by RET advocates of alternative energy plans which excluded nuclear energy kept the RET versus nuclear energy divide in sharp focus. This issue was principally put to rest in 1985.

Position of Some Residents

There were points during the period of this study where some resistance was evident to turbines owned by non-resident developers, poorly sited turbines, and larger turbines. The national government responded by setting residency and ownership requirements, putting repowering incentives in place to decommission older units, and strengthening the planning process with local authorities. Public participation and transparency have also been fundamental to project planning with, for instance, public comment periods on project environmental impact assessments (DEA, 2012). Denmark is now embarking robustly on a plan to scale wind power to 50% of total electricity by 2020. This plan is expected to rely on larger turbines and significant offshore development.

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[70] By some accounts, nuclear energy proponents used professional and personal attacks against individuals who advocated for RETs (Interview, 2012; Meyers, forthcoming).

Position Held by Some Regarding Wind Profits

In the 1990s, some opposition was voiced regarding the level of profits that wind power producers were making. Since 1992, wind generators would earn a guaranteed buyback rate of 85% from utilities, amounting to around 0.33 Dkk or 5.4 cents/kWh (contingent on coal prices), plus a CO_2 tax-related subsidy of roughly 0.10 Dkk/kWh.[71] In addition to these, private producers of RET generation would also receive a RET generation subsidy of 0.17 Dkk per kWh. In total, this then equaled 0.60 Dkk or roughly 9.8 cents per kWh. Earning from three sources can appear significant, especially if charged to tax payers. However, earlier analysis of comparative prices paid to wind power producers (see Costs), indicates that Denmark ranked in the middle range of four countries evaluated for such support (Soderholm and Sundquist, 2007).[72]

Danske Folke Party

Finally, the Danske Folke party, a far Right-wing minority party, has had a high profile in the last decade for catalyzing a policy shift away from wind power (Interviews, 2011-2012). According to interviewees, the Folke party provided necessary votes for a coalition and held an extremist minority foothold in the governments from 2001-2007. It is no longer in power.

[71] A European Commission press release at the time, indicated approval for the combined support, noting it equaled roughly 55% of the building and operating costs of the turbine (Sawin, 2001, citing EC, 1992).

[72] As noted above, periods tested included Denmark (1986-1999); Germany (1990-1999); Spain (1990-1999), and the UK (1991-2000) (Soderholm and Sundquist, 2007).

A Stake in the Game

When considering societal acceptance of wind power in Denmark, it is fair to say that certain constituencies opposed scale-up during a number of periods. Yet currently there does not appear to be any notable opposition. A key take-away from the interviews for this study was that those who promoted the energy transition had a deep-seated sense of commitment for and ownership of the change to a cleaner, more sustainable, and independent energy path. People often went beyond their basic roles and relationships to troubleshoot and shape ways for Denmark to become more sustainable, greener and energy independent. “Energy evangelists”, like those with the Tvind project, Svend Auken and Niels Meyer were regularly mentioned as agents of change. Most interviewees, including government officials and independent scientists, spoke of their contribution to wind energy adoption (and low carbon energy change) in terms showing a strong belief that their individual input mattered. If many people, not only in the early years, but today still feel this deep-seated and communal sense of contribution, then resisters will have a formidable challenge to overcome.

Industrial Development

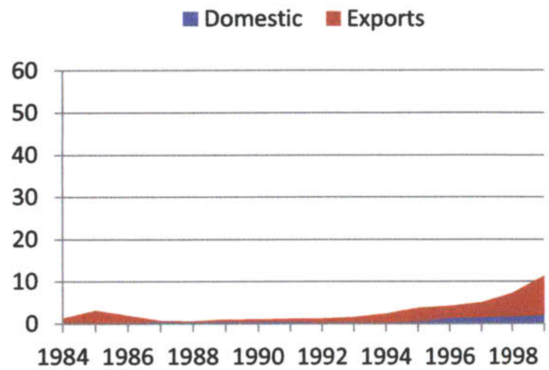
The Danish wind industry has been a world leader in wind turbine production and knowledge development for decades. In the 1980s and much of the 1990s, when total globally installed capacity grew slowly, it was not uncommon to see 4-6 Danish manufacturers ranked among the top ten largest manufacturers of wind turbines worldwide (Sawin, 2001). The emergence of other country leadership in installed wind capacity and manufacture, including that of Spain, Germany, India, China, and the

United States, has many direct links to Danish technology, knowledge sharing, and/or financing (Lewis and Wiser, 2007; Sawin, 2001; Interviews, 2011- 2012; Maegaard, 2009). Spanish wind turbine producer and wind power project developer Gamesa is one such outgrowth of a joint venture with Denmark's Vestas (Interviews, 2011).

In 2011, the international wind market equaled nearly 238 GW of installed capacity (compared to negligible numbers in the 1970s) (GWEC, 2012). Roughly 75 countries have wind markets with 21 having more than 1,000 MW installed (Ibid). The market remains highly competitive and has rising actors and markets in India, China, Mexico and Brazil (Ibid). Two Danish manufacturers, Vestas and Siemens, represent 28% of the total, cumulative installations worldwide based on turbine design (BTM, 2012). Amidst ongoing consolidation (leaders Vestas and NEG Micon merged) and heavy competition, two Danish manufacturers remain in the top ten with Vestas ranked number 1 (BTM, 2012).

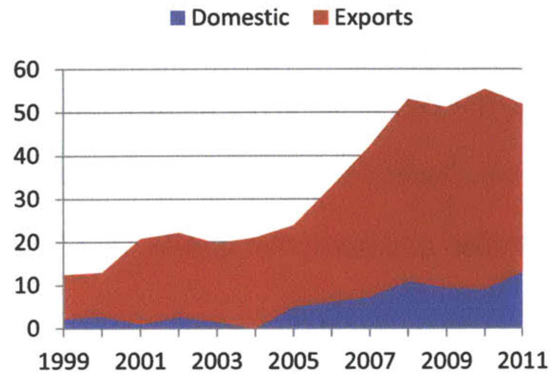
The following shows domestic and export earnings for the Danish wind industry from the early 1980s through 2011, based on information from the Danish Wind Industry Association and its predecessor, the Danish Wind Manufacturers Association (G9 and G10).

Figure G9: Annual Sales of Danish Wind Turbine Technology, 1984 to 1999
(Dkk billions, 1995)



Source: Data from Sawin, 2001, citing Danish Wind Turbine Manufacturing Association, 2000.[73]

Figure G10: Annual Revenue in the Danish Wind Industry, 1999 to 2011
(Dkk billions, not adjusted for inflation)



Source: Danish Wind Industry Association data, 2011 and 2012.

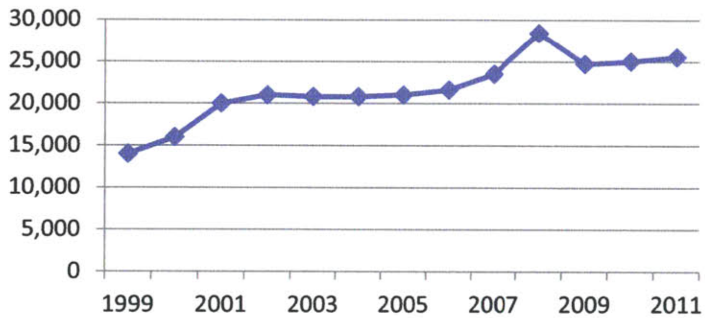
Note: The base currency years vary between the two sources. Additional assumptions may also vary.

While the base currency year and some other assumptions may vary, the overall trend is clear. Earnings have increased from negligible numbers of a newly emergent industry in the 1980s to 51.8 billion Dkk (roughly $8.8 billion) in 2011. For the majority of time, exports dominated the earnings with the exception of 1987 and 1988, following the decline in the California market. The period from 1970 to the early 1980s is also understood anecdotally to have focused on the domestic market development. From 1999 through 2011, earnings increased by a factor of 4.

[73] Sales, here, encompasses turbines, kits, spare parts, service and licensing income. Notably, Danish turbine component suppliers earned additional exports of roughly 800-1,500 million Dkk for 1995-1999 (Sawin, 2001, citing Danish Wind Turbine Manufacturing Association, 2000).

Employment of Danish wind industry employees currently stands at 25,520 (Figure G11), which demonstrates robust growth from the beginning of this study, when the industry did not exist (DWIA, 2012). Of these jobs, roughly 45% are manufacturing (Ibid). The DWIA observes a trend toward fewer, domestic wind turbine manufacturing jobs with Danish job creation now in other areas of the value chain, including consulting, installation and operation (DWIA, 2012).

Figure G11: Employment



Source: DWIA, 2012.

When considering wind technology and services exports in relation to total Danish exports, the wind sector's contribution has risen in the past decade from 2.5% in 2000 to 8.5% in 2009 (DWIA, 2011).

Direct experience underscores ongoing international interest in the Danish wind industry hub. When visiting and communicating with Danes, this researcher regularly heard about international delegations from areas, like China and Korea, studying the Danish wind energy hub. Teams from countries, including the United States and Spain, would travel to Denmark to study the Danish wind sector and its techniques for managing large-scale wind (Interviews, 20011-2012).

H. CONCLUSION

The wind power energy transition was not an assured priority for all Danes in the 1970s. Energy diversification, savings, and self-sufficiency were guiding principles for the government and industry, with nuclear energy singled out as the new form of energy to pursue. Yet Danish society tapped insights from an earlier era with widespread resourcefulness to produce a new industry and market. The Danish government reoriented to support the emergent pathway with strategic adaptation of key policies over much of the following 3+ decades to address uneven economics, technical change, and planning. This allowed continuous learning and development in 3+ decades with substantial scaling of wind power in the last 2 decades. Denmark has now embarked on a new and very aggressive, long-term green growth plan with wind power again on the rise.

APPENDIX

Danish Energy Transition Timeline

1962

- Danish Parliament gives authority to Ministry of Education to decide on the installation of nuclear plants

1970

- Ministry of Trade produces a report on large scale wind on the Danish power grid

1971

- ELSAM decides to build a nuclear power plant

1972

- Danish oil production commenced in the North Sea with the Dan field

1973

- Denmark joins the EEC

1973-1974

- Oil Embargo/first oil shock

1974

- ELSAM proposes an nuclear power plant in Jutland
- OOA is formed

1975

- OVE is formed

1975-1978

- Tvind Turbine built

1976

- DEA established
- 1st Energy Plan
- Alternative Energy Plan put forward by ATV
- Energy Research Program launched (publically funded R&D), including funding for wind research
- Electricity Supply Act – requires cost-based prices with allowance for reserves and depreciation; no reference to competition

1977

- Energy taxes introduced

1978

- Test station established for small wind turbines with approval scheme
- DWTO and DWIA formed
- Riso wind funded

1979

- Ministry of Energy established
- Energipakken: Investment grants for various technologies, including wind turbines through 1989 – 30% of capital cost; guarantees for grid connection and buy-backs;
- Large-scale test turbines (Nibe 1 and Nibe 2) erected by utilities
- Second oil shock, Iranian Revolution
- TMI nuclear accident
- PURPA passed in the United States providing favorable policy conditions for wind exports
- First agreements for natural gas supply to Denmark with Maersk Oil

1981

- Energy Plan 81 – 1st with a strong wind dimension
- Production subsidy begins
- Wind Atlas released
- Gorm field production begins (oil)

Early 1980s

- Exports begin to California wind market

1982

- Skjold field production begins (oil)
- RET Committee established

1983

- Alternative energy plan put forward
- Nordic Folkcentre for Renewable Energy established

1984

- Gas production begins
- Amend to Electricity Act of 1984, provided subsidies for grid-connected electricity from wind
- 1st voluntary purchase agreement - utilities and turbine owners/manufacturers
- New environmental regulations - 50% reduction of sulfur emissions by 1995; limits on the burning of straw

1985

- Danish turbines represent 50% of the California market
- Nuclear plans for Denmark withdrawn
- Denmark joins the EU
- Government-utility settlement for Danish power companies to install 100 MW of wind over next 5 years
- Restrictions established for 'local ownership' and investment share for turbines

1986

- Subsidies in the American market discontinued and in Denmark are reduced – 20+ bankruptcies for Danish wind turbine manufacturers follow and market consolidation ensues
- Chernobyl nuclear accident
- Danish Energy Agency and the RET Committee implement programs to foster decentralized CHP/DH
- New resource study released

1987

- Brundtland Report is released
- Government Committee on offshore regulatory conditions issues report

1990

- Energy 2000 plan
- Government-utility deal for 100 MW of wind power
- Danish Turbine Guarantee established
- Committee established to provide planning guidelines

1991

- Energy tax reform
- National wind map published
- Council for Renewable Energy established, including development program for RETS
- 1st offshore wind farm built worldwide – Vindeby is brought inline
- Denmark is self-sufficient in oil and gas

1992

- Wind Turbine Location Committee provides recommendations on increased coordination
- Systematic planning is instituted by the national government with direction to the local authorities
- Role of coops shrinks with change in planning procedures
- Government rule obligates power companies to develop/enhance the grid for wind additions
- CO_2 tax package passed
- Rio Summit

1993

- Svend Auken is named Minster of the Environment

1994

- Under a modified government, the Ministry of Energy and Environment are merged
- Municipal authorities ordered to indicate wind-suitable land in their plans (location and extent)

Mid 1990s

- Laws pertaining to farming sector open new prospects for farmers to own wind turbines; ownership now more mixed;

1995

- 2nd offshore wind project brought online - Tuno Knob
- Government Committee on offshore regulatory conditions reports

1996

- Energy 21 Plan
- Amendment to Electricity Supply Act – transition towards competition begins

1997-1998

- Offshore planning regulations are established with one-stop shopping
- Offshore plan of action prepared; mapping of potential sites identified roughly 4,000 MW of immediate potential
- Kyoto Protocol signed
- Requirement imposed on power companies to establish an additional 750 MW of offshore wind before 2008

1998/9-2002

- Liberalization of electricity and gas markets

1999

- Electricity Reform introduced - Electricity Supply Act (Law no 375, 2 June) plus political agreements among parties form the cornerstone for competition in the Danish electricity market
- New detailed Wind Atlas released

2000

- Denmark is 142% self-sufficient in energy
- Energy Savings Act adopted and Climate 2012 released
- EU approves electricity reform except for requirements on minimum price guarantees
- 1st large offshore wind project commissioned (40 MW), Middlegrunden

- Danes reconfirm decision not to join the Euro Zone in a referendum
- Liberalization of the gas market begins; Natural Gas Supply Act, July 1, 2000
- CO_2 quotas were set for the power producers (CO_2 bank)

2001

- Parliament approves Kyoto Protocol in May
- New Liberal-Conservative government takes office in November
- Liberalization and RET programs abolished
- Funding for wind power shifts to PSO paid by electricity consumers
- Parliamentary hearing, government postpones green cert implementation

2002

- Repowering program launched by pre-2001 administration leads to a short revitalization spurt in wind installations
- Offshore development and repowering sustain some growth in capacity
- Wind subsidies reduced, lead to almost full stoppage in RET development
- Repowering scheme ends

2003

- New price system goes into effect with a cap of .36 Dkk/kWh including CO_2 compensation
- Private investment in onshore wind come to a standstill

2004

- New incentive program with market premium adopted in lieu of green certificates Extra price paid for onshore turbine installation, if repowered
- Danish power sector restructured – distribution, transmission and production became independent sectors
- New Certification Scheme, based on IEC WT01 System for Conformity Testing and Cert of Wind Turbines, introduced to replace the Type Approval Scheme;

2005

- Energinet.dk, the Danish transmission system operator, is formed after liberalization of the electricity market and the merger of Eltra, Elkraft System, Elkraft Transmission, and Gastra
- Kyoto comes into force
- DEA starts new plan for siting offshore wind farms from 2010-2025
- Energy Strategy 25 is published

Mid- 2000s

- 3 working groups are formed for new wind siting - offshore, onshore and to position new industrially dev turbines (0 series)

2006-2007

- Municipal reorganization into new larger units

2007

- Government puts forward a vision for Denmark without fossil fuels
- Government proposes increase in wind subsidies

2008

- Political Agreement: raising of subsidies with cap on load years;
- Law No. 1392 of 27/12/2008 passed - implementation of the February 2008 Agreement

2009

- EU institutions adopt the 3rd Liberalization package to open power markets more and make them fairer

2010

- *Green Energy,* published by the independent Danish Commission on Climate Change Policy,

2011

- *Energy Strategy 2050* - Government plan outlines policy instruments to transform Denmark into a low carbon society with a stable and affordable energy supply
- Fukushima nuclear accident

2012

- Offshore wind farm project Kattegart (400 MW) to be implemented
- Political agreement by 95% of Parliament to advance a long-term, green growth strategy

Select Cost and Financing Aspects of Wind Projects

When considering the lifetime costs for wind power investments, one will often find that the preponderance of cost is associated with the up-front investment, as wind projects do not have fuel costs, and can have low variable operations and maintenance costs (O&M) (IEA Wind Task Force 26, 2011). Table A1 provides a typical breakdown of investment costs. Foundations and grid connections for offshore wind projects are substantially higher than corresponding on-shore costs, so cost distributions will differ (Ibid).

Table A1: Breakdown of Investment Costs for Onshore and Offshore Wind
(% of Total)

Costs component	Onshore %	Offshore %
• Turbine	71-76	37-49
• Grid connection	10-12	21-23
• Civil works	7-9	21-25
• Other	5-8	9-15

Source: Wiser et al, 2012, citing Blanco, 2009 and EWEA, 2009. Note: 'Turbine' covers transportation and installation. 'Grid connection' includes the connection, cables, and sub-station. 'Civil works' encompasses the foundation, road and building. 'Other' includes environmental impact assessments, permitting, engineering, licensing and monitoring (Ibid).

Power Markets – Vertically Integrated and Competitive Regimes

The type of power market structure or regime within which wind power integration occurs is significant since the regime defines the modes and types of power transactions, the flexibility and complexity of trades, as well as the governance relationship of actors.

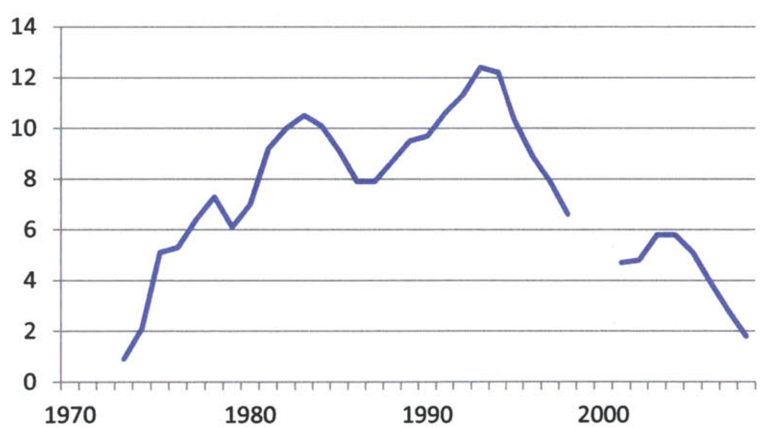
Historically, electricity has been managed within monopolistic markets where a single provider -- a vertically-integrated company -- typically owns and is responsible for serving market demand through generation, transmission, distribution and retail (Jamison et al, 2004). In this context, end-users are generally bound within a captive market structure with little alternatives, other than pursuing options like off-grid, distributed generation or non-use of monopoly-sourced electricity. The products, services and arguably the priorities of the vertically-integrated companies (VICs) may be influenced by regulators and/or other agencies of government. Prices are generally determined by regulatory prescription applied to a frequently non-transparent VIC strategy.

In contrast to traditional monopoly regimes, competitive markets enable multiple buyers and sellers to determine the price of a product through the equilibrium of supply and demand (Ibid). For electricity, this means that end-users have choices of service providers, possibly products, and that one company does not own/manage the sector.

Notably, both monopolies and competitive markets may have some similar externalities, such as information asymmetries.

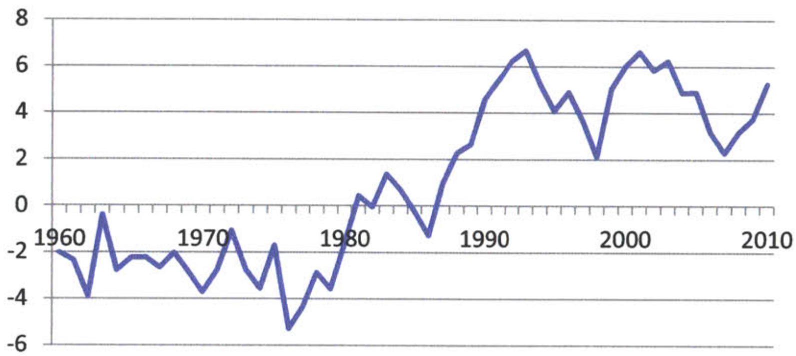
Additional Figures

Figure A1: Unemployment Rate %



Source: ILO Labor Statistics, Table 3A, accessed 6/13/12

Figure A2: Net Exports as % of GDP
(Exports – Imports, or External Balance on Goods and Services vs. GDP)



Source: WDI, 2012. External balance on goods and services equals exports of goods and services minus imports of goods and services.

Figure A3: Proven Oil Reserves
(Billion barrels)

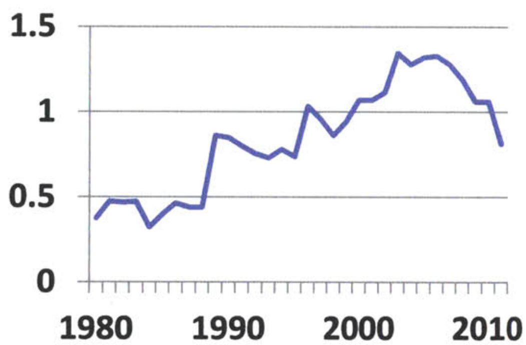
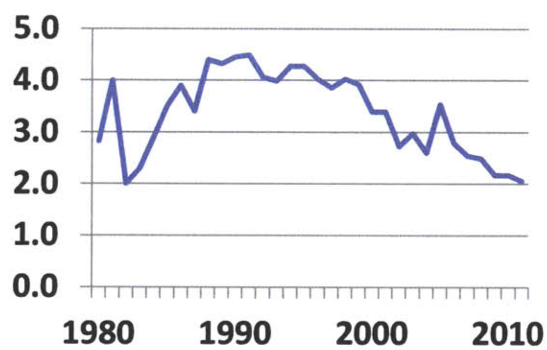


Figure A4: Proven Natural Gas Reserves (Trillion cubic feet)



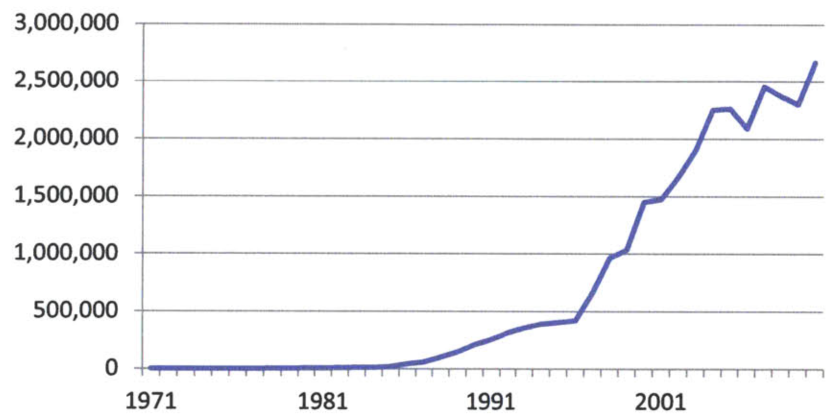
Source: EIA data, Country Statistics, 2012 for both charts.

Carbon Change

To gauge the carbon savings by adopting wind power, certain assumptions are made. First, wind is presumed to displace coal on a direct content basis, which does not account for factors, like reserves. While oil was the primary fuel in the early 1970s, it was quickly replaced by coal (other bituminous) (IEA, 2012).

Based on a coefficient methodology (see Figure A5 note), 28.3 million t CO_2 were cumulatively avoided by integrating wind power in the power sector in the period between 1970 and 2010 which equals 0.7 million t CO_2 on average per year. Figure A5 illustrates the estimated CO_2 emissions avoided with the substitution of wind power for coal.[74]

Figure A5: Avoided Carbon Emissions *(t CO_2)*



Source: Data for wind power in TPES from OECD/IEA (2012). Avoided CO2 emissions assumes wind power replaces coal on a direct content basis, applying a co-efficient of 95 t CO2 per TJ for substituted coal (Herald, 2003).

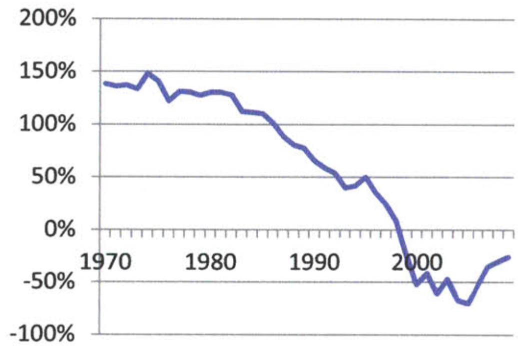
Import Dependence

In terms of energy self-sufficiency, Denmark evolved from near total dependence on imported oil to being an energy exporter. Figure A6 shows the change in net energy imports (imports minus exports) as a share of final energy consumption, declining radically. What was 133% in 1970 at the time of the first oil shock, peaked at 148% in 1974, and since declined to negative numbers (implying exports). Note: the amount can be above 100%, particularly if transfers, bunkers and conversion losses are not yet

[74] This excludes reserves.

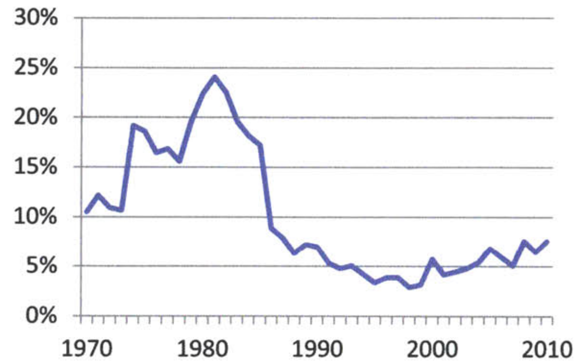
factored. This change does not track closely with Figure A7 which shows mineral fuel imports as a share of total traded imports in currency terms. Other commodities and factors like currency valuation play a role in that second chart.

Figure A6: Net Energy Imports as a % of Final Energy Consumed



Source: OECD/IEA data, 2012.

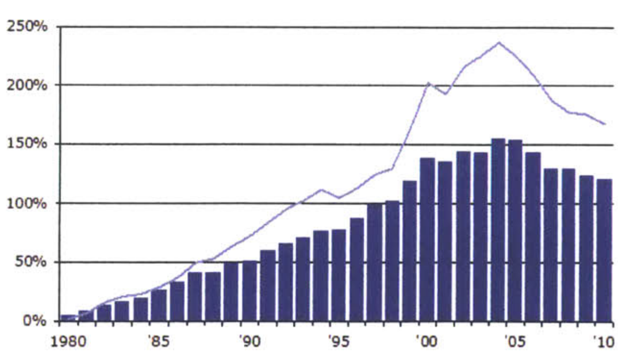
Figure A7 Mineral Fuels as % Imports (Trade Balance)



Source: UN Comtrade data, SITC Rev1, 2012.

Figure A8 provides a somewhat different view of the independence of Danish energy. Here, self-sufficiency can be seen to be attained in the late 1990s (blue bars) and that Denmark attained oil independence in the early 1990s (blue line).

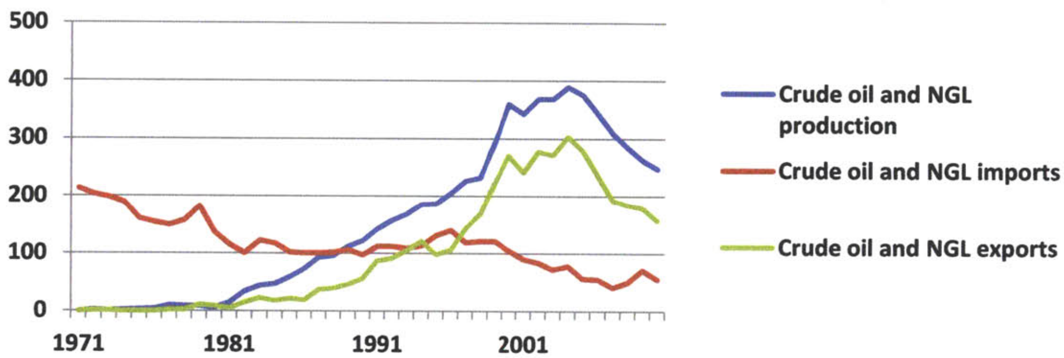
Figure A8: Degree of Energy Self-sufficiency



Source: DEA (2011). Energy in Denmark 2010; bars represent total energy and the line refers to oil.

Figure A9 breaks out details for crude oil and natural gas liquids production, imports and exports for most of the period studied. The fairly rapid rise in production between 1980 and 2000 tracks reasonably closely with exports.

Figure A9: Crude oil and NGL Production, Imports and Exports *(Thousand B/Day)*



Source: OECD/IEA data, 2012.

Table A2: Key Policy Tools used in Danish Wind Development

Sources: Unless otherwise noted include IEA reviews, DEA and BTM information, and Sawin, 2001.

Policy instrument	**Detail**	**Additional**
Research and development	Around 1976-1977, the Danish government established two R&D programs focusing on wind technology. The Energy Research Program fostered R&D on evolving aspects of wind energy. The Development Program included grants to form the Nordic Folk Centre in Jutland. (Nielsen, K., 2005; Sawin, citing IEA, 1987).	Energy Research Program (1976-) Development Program for RE (1976-2002/3)
Standards and	Beginning in the late 1970s, the Wind Test Centre at Risoe Laboratory set	

certification	standards for wind technology and certified turbine equipment. Government also instituted a new standards and approval scheme toward higher, end-to-end quality following the phase-out of the investment tax credit in 1989 (Nielsen 2005, 2001). With liberalization, certification services were opened to 3rd parties.	
Investment credits	For the period 1979-1989, an investment tax credit was paid to procurers of certified wind turbines as a % of the total capital cost of equipment.	May 1979: 30% Jan 1981: 20% Jan 1982: 30% Jan 1985: 25% June 1985: 20% Jan 1986: 15% Jan 1989: 10% Aug 1989: 0% (Nielsen 2005, citing Energimil-joradet, 1998)
Guaranteed markets	Beginning in 1985, the government and utilities brokered deals for the utilities to install large-scale wind projects. Up to 2001, the deals were met with the state of the art wind technology by Danish manufacturers (Nielsen, K., 2005). Since then, auctions have been used.	1985: 100 MW 1990: 100 MW 1996: 200 MW 1998: 750 MW (Vasi, 2011)
Taxes	Taxes were imposed in 1977 to cover additional oil products and electricity, and in 1982 to cover coal. Natural gas was also taxed at low rates less consistently.	1986: Oil taxes rose significantly. 1991: Reform with environmental priority - energy and carbon tax
Industrial/ international	An export guarantee scheme of 50 million Dkk was established for wind turbine	

development of wind power	manufacturers in 1992-93 (Nielsen, K., 2005). DANIDA and the loan program of the 1990s supported green growth and various wind power projects. DANIDA focused on projects in developing countries (Sawin, 2001).	
Planning	Ad hoc planning was done in the period 1970-1990. In 1991, a committee was established to determine wind development sites for utilities to meet project quotas (Nielsen, K., 2005). From 1994 onwards, planning for wind project siting was managed in a more integrated and long-term manner with measures at the local/municipal and national levels. In 1998, planning evolved further with separate tracks for inshore and offshore development, leading to one-stop shop for offshore wind. *See* also energy plans below.	• Onshore <150 MW, municipality oversight • Onshore >150 MW, DEA oversight • Offshore, DEA oversight
Energy Plans	**1976: Energy Policy Act** Security from international energy crises; improved supply security **1981: Energy 81** Socio-economic and environmental aspects of secure energy **1990: Energy 2000** Commitments for CO_2 reduction; expansion of RETs **1996: Energy 21** New targets for RETs (30% of Electricity from RETs by 2025) **2000:** **Energy Savings Act** – conservation **Climate 2012** – Update on Energy 21,	

	stabilization of CO2 **2007: Vision for fossil free future** **2011: Energy Strategy 2050** (formalized in 2012 agreement) **2012 Agreement: Low Carbon Future** (*see* Targets)	
Targets	Select targets for RETs, Wind, CO_2 **Kyoto:** Reduce GHGs by 21% in 2008-2012 vs. 1990 levels; National Commitment: Reduce CO_2 by 20% of 1988 levels by 2005 **1990** • 10% of electricity from wind power by 2005, implying an installed base of 1,500 MW • Reduce CO_2 by 20% by 2005 from 1988 levels; **1996:** • 50% of electricity from wind by 2030 **2011:** Energy Strategy 2050 • RE should cover 60% of electricity consumption by 2020 (Hvelplund, 2011, citing DEA 2011) • Wind should = 50% of electricity by 2025 (Mills and Manwell, 2012) • 100% energy consumption from RETs by 2050 **2012: Low Carbon Future** 35% of total energy from RETs by 2020 (half from wind power) Cut GHGs by 34% of 1990 levels by 2020 Reduce consumption by 12+% vs. 2006 level	
Ownership limits	In 1984, limits were put in place on turbines so that owners must live within a range of 3 km from the turbine (Hvelplund, 2011). This underwent widening iterations and was relaxed with	

	liberalization. Rules now stipulate a turbine project must allow locals an opportunity to participate up to 20%.	
Power purchase agreements for wind generation	Since the late 1970s, electric utilities, wind turbine manufacturers and wind turbine owners had voluntary agreements on the purchase price of grid-connected wind generation with encouragement from the government. This approach broke down in the early 1990s, so the government set a fixed price per kWh in 1992 at 85% of the utility cost.	
Environmental/ CO_2 tax exemptions, credit	In 1984, the government instituted measures exempting wind producers from an electricity consumption tax on a per kWh basis. A renewable energy generation credit was also established on a per kWh basis. In 1991, a CO_2 credit was put in place for all RET producers and an additional subsidy was implemented for wind, biogas, and water-based power. The latter was removed in 2000 (Nielsen, K., 2005).	
Repowering	Introduced in the 1990s and again in the past decade - additional support is paid per kWh to replace older equipment with more efficient turbines and consolidate turbines in more optimal resource sites.	
Grid management of wind power	The government required grid access in a 1979 law. Early grid connection costs were ad hoc. In 1992, the government mandated that costs were split between turbine owners and electric utilities.	
Production Payment	**1991-2002** 0.17 Dkk/kWh subsidy + 0.1 Dkk/kWh (utilities and others) (Sawin, 2001) **2003/4-** Replaced by market premium:	

Information	Studies and reports on wind resources, technology performance and cost info, etc	

Excerpt from the DEA's History of Danish Support for Wind Power
(Undated, (http://www.ens.dk/en-us/Sider/forside.aspx)

Existing wind turbines bought before the end of 1999
Production from wind turbines bought before the end of 1999 is sold in the market by the TSO (transmission system operator) and the producer receives a fixed feed in tariff of 8 c€/kWh for a number of full load hours (25.000 full load hours for turbines below 200 kW, 15.000 full load hours for turbines below 600 kW and 10.000 full load hours for turbines larger than 600 kW). After the full load hours are used, the feed in tariff is 5.8 c€/kWh until the turbine is 10 years old. After this, the producer must sell the power in the market and receives a price premium of maximum 1.3 c€/kWh until the turbine is 20 years old. The sum of market price and price premium is limited to maximum 4.8 c€/kWh. An additional price premium of 0.3 c€/kWh is paid to cover balancing costs in the electricity market.

2000 - 2002
Production from wind turbines connected to the grid from 2000 to 2002 is sold in the market by the TSO and the producer receives a fixed feed in tariff of 5.8 c€/kWh for 22.000 full load hours on land or 10 years at sea. After the first period, the producer must sell the power in the market and receives a price premium of maximum 1.3 c€/kWh until the turbine is 20 years old. The sum of market price and price premium is limited to maximum 4.8 c€/kWh. An additional price premium of 0.3 c€/kWh is paid to cover balancing costs in the electricity market.

2003 – 2004
For wind turbines connected to the grid in 2003 or 2004, the producer must sell the power in the market and receives a price premium of maximum 1.3 c€/kWh until the turbine is 20 years old. The sum of market price and price premium is limited to maximum 4.8 c€/kWh. An additional price premium of 0.3 c€/kWh is paid to cover balancing costs in the electricity market.

2005 – 20th February 2008
For wind turbines connected to the grid from 2005 to 20th February 2008, the producer must sell the power in the market and receives a fixed price premium of 1.3 c€/kWh until the turbine is 20 years old. An additional price premium of 0.3 c€/kWh is paid to cover balancing costs in the electricity market.

21st February 2008 –
For wind turbines connected to the grid after 21st February 2008, the producer must sell the power in the market and receives a fixed price premium of 3.4 c€/kWh for the first 25.000 full load hours. An additional price premium of 0.3 c€/kWh is paid to cover balancing costs in the electricity market. This support applies both to wind turbines on land, and wind turbines at sea which are not covered by tenders.

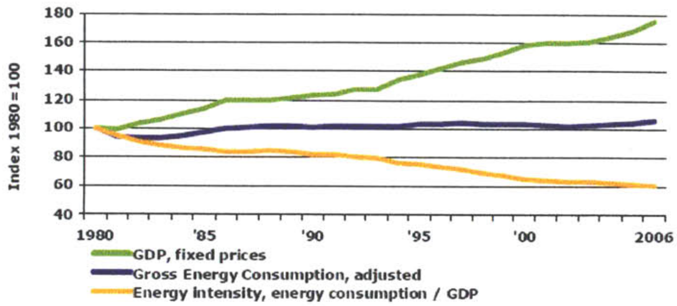
Additional support for replacing old turbines with new
New wind turbines which replace small turbines receive extra 1.1 c€/kWh for the first 12.000 full load hours. This additional support aims at replacing old turbines which often occupy the best locations. Between 1999 and 2003 the support under this scheme was 1.6 c€/kWh for the first 12.000 full load hours.

Table A3: Grid Interconnections

Eastern Denmark	**Western Denmark**
Sweden (link to the Nordic grid) 1951-1964: two 132 kW AC connections 1973: 400 kV AC connection 1985: 400 kV AC connection Capacity of approximately 1900 MW	**Sweden** 1965: 250 kW DC connection 1988: 250 kW DC connection Capacity of approximately 740 MW
Germany 1995: 400 kV DC connection Capacity of 600 MW	**Germany** 1961-1965: 220 kV AC connection 1978: 400 kV AC connection Year not reported: 150 kV AC Capacity determined by congestion, typically 1,500 MW southbound and approximately 950 MW northbound
	Norway 1972-75: 250 kV DC and 270 MW 1992: 350kV DC and 500 MW Capacity: 1,040 MW
Great Belt Power Link (Eastern and Western Denmark) 2010: 400 kV DC 600 MW	

Source: Energinet.dk, 2012.

Figure A10: Danish Energy Consumption, GDP and Energy Intensity



Source: DMCE (2008).

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Chapter 6:
French Nuclear Energy: Concentrated Power

"No coal, no oil, no gas, no choice...." French maxim, mid-1970s[1]

A. INTRODUCTION

Well before nuclear energy was used to power submarines or to fuel power plants, scientists and national decision-makers questioned how to harness its incredible power (Marcus, 2010; Goldschmidt, 1962). Raoul Dautry, the first Administrator-General of the French Commissariat a l'Energie Atomique, called nuclear energy a 'diabolical marvel', saying that to master its terrifying forces with a humane application would bring honor to France.[2]

In the following pages, France's mastery of this power is explored. The chapter begins by surveying the basics of nuclear power, and then highlights aspects of the French nuclear energy transition, focusing on the civilian application of nuclear energy in the power sector. As with other chapters, this one identifies key innovations and adaptations, then examines major drivers, barriers, and indicators of the energy transition.

[1] Interviews, 2011-2012; Palfreman, undated.

[2] Hecht, 2009, citing EDF, accessed by Hecht, 2007.

B. BASICS of NUCLEAR POWER and TECHNOLOGY

Today's use of nuclear energy in the power sector begins with the controlled and sustained release of energy in the process of nuclear fission. In an induced chain reaction, atomic nuclei are split, producing heat which, as steam, drives a turbine to provide electricity (Barre, 2008; Sovacool, 2010).[3] Considerable amounts of energy are produced in this process which can be structured to be self-sustaining (Tester et al, 2005). A simplified analogy of annual power plant fuel requirements illustrates the striking difference in orders of magnitude for energy releases from chemical reactions and nuclear fission. Factoring for different fuel concentrations, a 1,000 MWe power plant utilizes about 3,000,000 tons of coal versus 36 tons of enriched uranium (~1 ton of U-235) for a light water cooled reactor (Ibid).

For nuclear fission to occur in a nuclear power plant, basic material inputs include a fuel, moderator, and coolant (Sovacool and Valentine, 2012). Fuel feedstock includes uranium, plutonium, and thorium with uranium being the most common (Ibid; Barre, 2008).[4] These can be utilized as an oxide, metal, carbide or nitride, yet must be in a form where isotopes may split by fission (i.e. be fissile) (Barre, 2008). Uranium 235 (U-

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[3] The nuclear fission process differs from nuclear fusion in that the latter brings atomic nuclei together to produce energy. Another distinction lies in the technological and commercial maturity of the two processes. Fusion is still very much in a pre-commercial stage of development after more than 50 years of study, and worldwide R&D expenditures possibly on the order of $30 billion (current $, 2006) (Holdren, 2006). By contrast, fission has been commercially used in the power sector since the 1950s (World Nuclear Association/WNA, 2012; Chapter 1).

[4] Combinations of uranium and plutonium are also used. Thorium is not currently utilized at an industrial scale, but is the focus of research in areas that are rich in the resource, namely India (Pradhan, 2012; Barre, 2008).

235) is the only naturally-occurring fissile isotope (Ibid). Alternative fissile isotopes, such as Plutonium 239 (Pu-239) and Uranium 233 (U-233), may be produced from naturally-occurring fertile isotopes, notably Uranium 238 (U-238) and Thorium 232 (Th-232) (Ibid).[5] The determination of fuel type is usually contingent on the moderator and reactor technology (Sovacool and Valentine, 2012).

A moderator is material which slows fast neutrons released from nuclear fission, thus enabling a nuclear chain reaction to occur (Barre, 2008; Sovacool and Valentine, 2012; Interview, 2012). Reactors can generally be distinguished by moderators. For example, fast breeder reactors do not require a moderator, whereas thermal neutron reactors, such as those with light water technology (discussed below), do (Ibid).

The remaining primary input in a nuclear reactor is a coolant. It typically is pressurized water, but can also be a gas or a liquid metal, like molten sodium (Ibid). The coolant absorbs heat released from fission and produces steam which powers a generator (Ibid).

While there are many theoretical combinations of fuel, moderators and coolants in a nuclear reactor (Barre, 2008), today's commercial plants broadly reflect thermal neutron technology which can be classified in the following categories by the moderator.

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[5] For more extensive discussion of isotopes, as well as fertile and fissile materials, see Barre (2008) and Kravit et al (2011).

Light water reactors (LWRs) account for 80+% of the nuclear power plants (NPPs) globally in use today (Sovacool and Valentine, 2012, citing Froggatt, 2010). The prevalence of LWRs can be largely explained by their use of common water as a moderator (Barre, 2008; Sovacool and Valentine, 2012). Water serves not only as a good moderator and coolant, but is relatively abundant, inexpensive, and easy to manage (Ibid). Such reactors must be sited near a river or sea, allowing the body of water to serve as a heat sink (Barre, 2008; Interview, 2012).[6]

The LWR reactor class can be divided into two primary groupings: Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs). With BWRs, the coolant water is converted into steam within the reactor vessel. The steam is then conveyed via a pipe to drive a turbine (Sovacool and Valentine, 2012) (Figure B1). In PWRs, the coolant water is circulated at high pressure between the reactor core and a steam generator, coming into contact with secondary feed-water that is heated to generate steam and power a turbine (Ibid) (Figure B2). The use of common (light) water as a moderator by LWRs requires enriched, rather than natural uranium; otherwise, too many neutrons would be absorbed (Ibid). While enriched uranium is the standard fuel with LWRs, some PWRs use a blend of uranium and plutonium known as mixed oxide (MOX) (Barre, 2008).

[6] A heat sink transfers thermal energy from a higher temperature medium to a lower one. Fourier's law of heat conduction and Newton's law of cooling are the basis for this.

Figure B1: Boiling Water Reactor

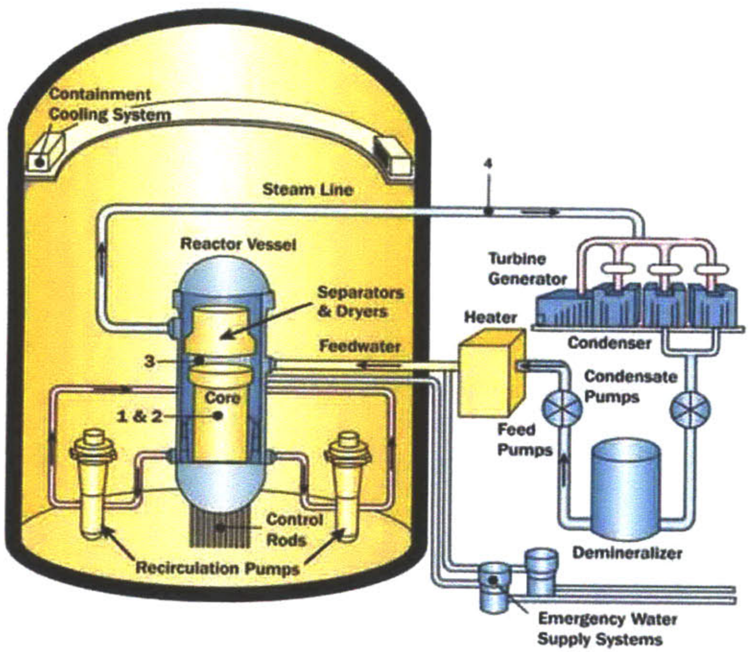
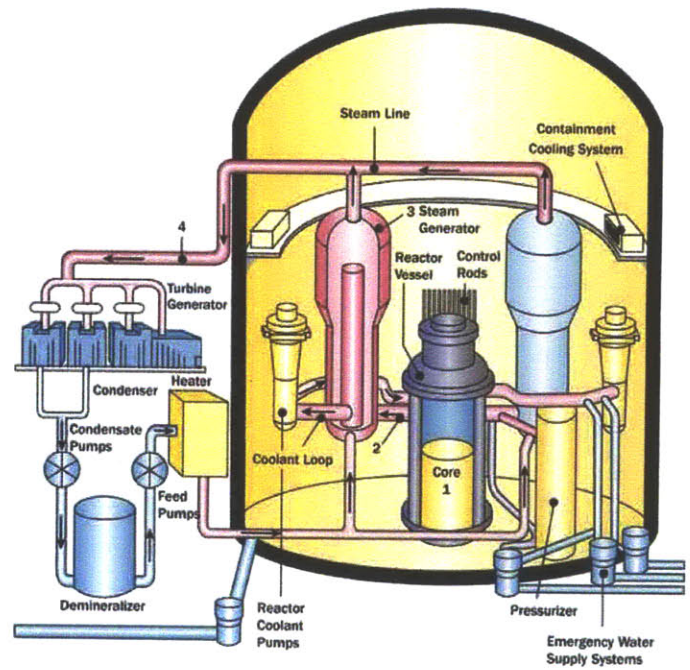


Figure B2: Pressurized Water Reactor



Source: US NRC, 2012 for both diagrams.

Another category of commercial reactor is the heavy water design (HWR) that is found in Canada Deuterium Uranium models (CANDU) (Barre, 2008). This technology utilizes D_2O (heavy water) as the moderator and frequently as the coolant (Ibid). Heavy water contains an elevated concentration of molecules with deuterium atoms (Anantharaman et al, 2011) and is costly to produce (Sovacool and Valentine, 2012; Interview, 2012). Such a moderator allows the HWRs to skip the uranium enrichment process and operate with less expensive, natural uranium (Barre, 2008). Roughly 8% of the world fleet employs this type of reactor technology (Sovacool and Valentine, 2012).

A third category of commercial reactor technology is a gas-cooled design which utilizes graphite as the moderator (Ibid, Barre, 2008). Like CANDU models, this model can also run on natural uranium. Its shorthand nomenclature in French - UNGG for *Uranium Naturel Graphite Gaz* (NUGG in English) – derives from this. The design is considered to be relatively safe because of its low power density and use of gas as a coolant (Sovacool and Valentine, 2012). An advantage to this design is in fuel loading and unloading that can be done while the reactor is operating (Ibid; Barre, 2008). A disadvantage in terms of cost and technical challenge with this model's first generation was that fuel needed to be replaced regularly (Sovacool and Valentine, 2012). More recent versions have reduced this problem. However they have not attained the same economies as LWRs (Ibid).

A final category of reactor is the water-cooled, graphite moderated reactor (Reaktor Bolshoi Moshchnosti Kanalnye or RBMK). This class shares some characteristics with the above, gas-cooled graphite moderated design, since they both use graphite as the moderator, and the fuel loading/unloading may be done as the reactor is operating (Barre, 2008). The RBMK differs from its gas-cooled counterpart in that conventional light water is used instead as the coolant (Ibid). RBMK technology is also subject to power surges, and notably containment buildings are not typically used (Ibid). This reactor technology class is widely known for its association with the Chernobyl nuclear accident, and was instrumental in the Soviet Union for generating weapons-grade plutonium to be used in its nuclear arsenal (Ibid).

Nuclear Fuel Measurement and Uprating

The level of energy extracted from nuclear reactor fuels is typically measured in terms of a burn-up rate. Presented as GW days per ton of fuel, this indicator reflects the thermal energy released by nuclear fuel as a ratio to the mass of fuel material consumed (Anantharaman et al, 2011).

Another concept in nuclear technology is uprating. If utilities want to increase the power output of a nuclear plant, they may undertake measures to uprate. This typically entails the operator refueling the plant with more enriched fuel or a higher percentage of new fuel in order to attain an increased power level (NRC, 2010-2012). Operating at a higher power level generally produces greater amounts of steam and water flows, so components, like pipes, valves and heat exchangers will require modification (Ibid).

Nuclear Technology Attributes

Nuclear power plants are generally deployed as highly centralized, stable and somewhat inflexible technology with large-scale plants that are on the order of 1,000 MW in size. In recent years, smaller modular plants have received some attention (MIT Energy Conference, 2011; WNA, 2012), but it is not clear that they can provide economies of scale in production or advantages in other areas to offset the economies of scale of conventionally large plants (Bunn and Malin, 2009).

Fuels

Uranium, the most common feedstock for nuclear fission, is found in rock and the sea (WNA, 2011). In 2010, global production equaled 53,663 tonnes of uranium, an increase of 6% over 2009 (Ibid).[7]

When considering uranium for nuclear power plant use, the amount of fissile material matters. Natural uranium, used in NUGG reactors, contains 0.71% of the fissile isotope U-235, whereas U-235 used in LWRs must be enriched to a concentration of 3-5% (WEC, 2010). The enrichment process produces substantial quantities of depleted uranium tailings with different U-235 concentrations, usually in a range of 0.25%-0.35% (Ibid). When uranium prices are high, it may be economically feasible to re-enrich the tailings (Ibid).

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[7] Uranium's resource availability is classed by price bands. Total identified resources as of January 1, 2009 equaled 5.4 million tonnes in the <$130/kg U category (<$50/lb U_3O_8) and 6.3 million tonnes in the <$260/kg U (< 100/lb U_3O_8 category) (OECD/NEA, 2010).

Fuel Cycle

The nuclear fuel cycle involves a series of fuel processing stages. The focus, here, is principally on uranium, as a feedstock. On the front-end are stages for uranium mining, milling, converting, enrichment and fabrication. These essentially occur before power is generated in a reactor (Barre, 2008). The fuel cycle back-end includes reprocessing and/or storage and disposal of spent fuel. Broadly speaking, management of fuel entails an open cycle (i.e. once-through) or a closed cycle approach (Ibid). In open cycles, spent fuel is treated as waste with no attempt to recover unused fissile material; whereas in closed cycles, spent fuel is re-treated for continued use (Ibid; Anantharaman et al, 2011).

Front-end Fuel cycle

In the first stage of the fuel cycle, mining approaches range from forms of direct excavation to in-situ extraction. The first approach, underground mining, entails the digging of long, thin shafts to extract uranium from underground seams (Sovacool and Valentine, 2012). By contrast is the more prevalent open pit mining which involves the removal of rock layers to extract to the underlying uranium (Ibid). Another approach is In-situ leaching which bathes underground uranium deposits with acidic or alkaline solutions, at which point, the uranium ore is pumped to the surface (Ibid; Sovacool, 2008b; WNA, 2012). The third approach highlights a number of important tradeoffs, as less time and cost are typically involved, yet more water is used (up to 7-8 gallons of water per kWh of nuclear power generated) (Sovacool and Valentine, 2012, citing US DOE, 2006).

As with fossil fuel extraction, uranium mining can have a significant environmental impact. To extract and use a typical amount of uranium in a nuclear reactor for a year (25 tons), an estimated 500,000 tons of waste rock, 100,000 tons of toxic mill tailings, 144 tons of additional solid waste, and 1,343 m^3 of additional liquid waste are also produced (Sovacool and Valentine, 2012, citing Thorpe, 2008).

Once uranium is extracted, it must undergo processes to eliminate debris and further prime it for fuel use (Sovacool, 2008b). The milling process breaks down the mined material with an acidic or alkaline wash, leaching the uranium from the ore (Ibid). Resulting powder is roughly 75% uranium oxide (U_3O_8), known as yellowcake (Ibid). Residual material, namely oxide and tailings (i.e. ore with rock material), is radioactive, so must be treated (Ibid; WNA, 2012). Solutions, like acids used in milling, also require neutralization (Sovacool, 2008b, citing Fleming 2007; and Heaberlin, 2003).

The next stage of the fuel cycle entails the conversion of uranium oxide into uranium dioxide which can then be utilized in reactors suited for natural uranium (WNA, 2012). For plants requiring enriched uranium, the feedstock must be transformed into uranium hexafluoride for added processing (UF_6) (Ibid; Sovacool, 2008b).

Uranium enrichment increases the proportion of U-235 to U-238 material in nuclear fuel (Anantharaman et al, 2011; Sovacool and Valentine, 2012, citing Yudin, 2009). Two commercially popular approaches include diffusion and centrifuge separation (WNA, 2012; Sovacool and Valentine, 2012).[8] The diffusion approach, which recently accounted for roughly 25% of the global enrichment capacity, entails the filtering of pressurized UF_6 through a porous membrane in a cascade process involving roughly 1,400 stages (WNA, 2012). The second approach, using centrifuge technology, is more popular today (Ibid, Sovacool and Valentine, 2012). It entails the funneling of UF_6 gas through vacuum tubes which rotate in cylinders at rapid speed (Sovacool, 2008b, citing Uranium Information Centre, 2007). Centrifugal forces then separate U-238 and U-235 (Ibid).

Reactor fuel using enriched uranium generally undergoes a subsequent fuel fabrication process to become UO_2 where it is pressed and sintered (baked) into pellets (WNA, 2012; Sovacool and Valentine, 2012). The pellets are incorporated into fuel rods that are then combined in fuel assemblies for use in a reactor (Ibid).

Back-end Fuel cycle

Fuel in nuclear power plants must be periodically replenished to replace built-up fission by-products with new uranium (Ibid). In conjunction with this, reprocessing may occur. Reprocessing entails the separation of spent fuel into 3 streams: uranium, plutonium and waste.[9] Separated uranium can then be channeled through the conversion process

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[8] Another process entails the repurposing of nuclear weapons materials (WNA, 2012; WEC, 2010).

[9] Reprocessing approaches include Purex and Pyroprocessing, among others:

- Purex or plutonium uranium extraction entails the extraction of chemically pure plutonium. Originally, this process was utilized to prime weapons-grade material, once again on the front-end for enrichment. Plutonium may also be used. If plutonium undergoes fuel fabrication, it can be utilized in mixed oxide fuel (MOX), as an alternative to enriched uranium fuel, or in weapons (WNA, 2012; Sovacool and Valentine, 2012). In the latter instance, weapons-grade plutonium must come from under-irradiated spent fuel (Interview, 2012). Notably, plutonium from LWR spent fuel has never been used for weapons (Ibid).

Prior to reprocessing or long-term disposal, interim storage of spent fuel can be accomplished either in wet or dry form. Wet storage requires the immersion of spent fuel assemblies in water within concrete pools encased in steel (WNA, 2012; Sovacool and Valentine, 2012). The water not only cools the fuel assembly, but also provides a shield from radiation. Dry storage, used for material after it has been stored in wet storage for a period of years, employs gas or air as a coolant with metal or concrete as a barrier (Sovacool and Valentine, 2012).

Long-term storage is much discussed, but has not yet happened, as there are no appropriate disposal facilities in place (Ibid; WNA, 2012, see Environmental, Public Health, and Other Concerns below). An option currently receiving much scrutiny

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and has since been applied to the civilian power sector (Stanford et al, 2009; Hannum et al, 2007). It is expensive and requires tighter security procedures to minimize proliferation risk (Ibid).

- Pyroprocessing was developed in the 1980s and 1990s to allow for reprocessing without the risk of generating weapons-grade plutonium (Ibid). According to some, the waste from this approach becomes "essentially harmless" within a few hundred years compared to the 'more standard' period of tens of thousands of years (Ibid).

involves the use of geological repositories for sequestering waste. Such locations minimize the chance that radioactive substances will diffuse into the atmosphere or expose humans to dangerous levels of radiation (Sovacool and Valentine, 2012).

When discussing nuclear waste management, it is useful to bear in mind that lengthier durations of interim storage generally mean that waste will be more manageable for long-term storage (WNA, 2012). This occurs because there is a progressive diminution of radioactivity and heat production (Ibid).

Decommissioning

Nuclear reactors and uranium enrichment facilities must be decommissioned as part of their closure processes. A plant must cool, usually 50-100 years, at which point it can be dismantled for final disposal (Sovacool, 2008b; 2010). Estimates of the energy needed for decommissioning indicate the process can exceed that of the original construction by as much as 50% (Sovacool, 2008b, citing Fleming, 2007). In terms of costs, there is limited experience with decommissioning to date. Examples from the U.S. and U.K. point to costs ranging from $300 million to $5.6 billion per facility (Sovacool, 2010).

Water

In addition to the use of water in milling and mining processes, substantial amounts are needed for running conventional nuclear reactors (Sovacool, 2010). Relative to other power generation plants, nuclear facilities use the most water (Ibid). However, some water can be reused. This condition becomes important when droughts occur or where water is scarce, as it can constrain nuclear power as an energy option.

Environmental, Public Health and Other Concerns

Use of nuclear energy invariably raises questions about environmental, health, and societal implications. The following discusses a number of specific areas, including nuclear accidents, radiation exposure, waste, proliferation and sabotage.

Nuclear Incidents and Accidents

When considering nuclear power safety, it's useful to understand distinctions related to incidents and accidents. A nuclear incident is an event or technical failure during standard plant operations that does not produce off-site releases of radiation or considerable damage to equipment (Sovacool, 2011a and 2011b). By contrast, a nuclear accident refers to the same operational context, yet one in which off-site releases of radiation or considerable damage occurs to plant equipment (Ibid). The International Nuclear and Radiological Event Scale (INES) ranks the severity of nuclear and radiological events with a scheme where Levels 1-3 are 'incidents', and Levels 4-7 are 'accidents' (Ibid). Quantifying and ranking such impacts oversimplifies their complexity. Nonetheless, the gauge provides a working means to compare and discuss events. A Level 7 accident would entail "a major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures" (Ibid, citing INES).

Looking more closely at accident examples, the Fukushima event was a Level 7 accident with an early estimate of 21 deaths and $152 billion in costs ($ 2010) (Sovacool, 2011a). This contrasts with the 1986 Chernobyl accident which also was level 7 and is estimated (albeit debated) to have included 4,056 deaths and $7.2 billion ($2010) in costs (Chernobyl Forum, undated; Sovacool, 2011a). Finally, the Three Mile Island (TMI) accident was a Level 5 accident with estimates indicating no fatalities and costs of $2.6 billion ($2010) (Sovacool, 2011a).

Naturally, the way that nuclear safety is framed shapes the discourse and decision-making. Technical failures, equipment damage, and releases of radiation can occur in the context of power plants shutting down, at research reactors, with military testing, or during different stages of the nuclear fuel cycle that are not covered within nuclear power assessments (Ibid). For instance, accident-related releases of radioiodine occurring at the Savannah River reprocessing plant in South Carolina (USA) to date have exceeded that of TMI by a factor of 10 (Ibid). There is also the case of a break in the uranium mine tailings dam in New Mexico in 1979, which produced the single largest release of radioactive material in the United States (excluding military weapons testing) (Ibid). In this example, water was left undrinkable for 2,000 people living in the nearby Navajo reservation, and farm animals were heavily contaminated with Lead-210, Polonium-210, Thorium-230, and Radium-236 (Ibid, citing Sovacool 2011).

Larger system interdependencies also hold relevance for nuclear safety, as was evident with the Fukushima accident. In that particular example, an earthquake was followed by a tsunami, which flooded areas of Japan, leaving the back-up system for the Fukushima nuclear plant without power (WEC, 2012). In another example, the 2003 black-out in the Eastern United States revealed inadequate maintenance of back-up systems for more than a dozen nuclear power plants in the U.S. and Canada (Sovacool, 2011b).

When considering nuclear safety, responsibility lies with facility operators to address issues and ensure safety, under the oversight of national nuclear authorities (Bunn and Malin, 2009). Complementing this is the international safety regime, consisting of the Convention on Nuclear Safety; other safety and liability agreements; organizations focused on nuclear safety; and broad, mostly voluntary standards (Ibid).[10] In practice, the international regime adds important value to the nuclear safety landscape, yet is based on limited real authority and voluntary compliance (Bunn and Heinonen, 2011). As a consequence of events, like Fukushima, nuclear safety has received increased attention leading to additional testing and adaptations in standards, design, training and processes (WEC, 2012; WNA, 2012; Union of Concerned Scientists, 2012; Pouget-Abadie, 2012). Nevertheless, the changes are uneven and cannot guarantee against subsequent issues.

A study of 279 accidents across fuel types from 1907 to 2007 found that the three most fatal accidents worldwide involved hydropower, nuclear power and gasoline (Sovacool, 2008a). The structural failure of the Shimantan hydropower facility in China in 1975, for

[10] The Convention on Nuclear Safety entered into force in 1996 and is designed for participating States with land-based, operating nuclear power plants to commit to maintaining a high degree of safety with benchmarks set for the group (IAEA, 2012c).

example, caused the greatest number of deaths with 171,000 fatalities ($9 billion in property damage) (Ibid). The Chernobyl accident, noted earlier, followed next in terms of fatalities (Ibid). A petroleum pipeline explosion in the Niger Delta, Nigeria in 1998 ranked third for fatalities with 1,078 deaths ($54 million in property damage) (Ibid). Considering variables other than fatalities, the study also found that natural gas was the highest among fuel types for the number of accidents (33%), whereas nuclear energy ranked highest for costs from damages, accounting for 41% of all property damage among accidents studied (Ibid)

Radiation

Central to concerns over nuclear accidents is exposure to ionizing radiation. Such radiation can damage or modify living cells, leading to death (Chernobyl Forum, 2006). Living organisms may be exposed to this from natural sources, like cosmic rays, as well as anthropogenic sources, like certain medical treatments, x-rays, and nuclear power use (Ibid). One gauge for exposure is the sievert, often shown as millisieverts, to describe what is deemed by some to be normal exposure. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimates that humans are annually exposed to 2.4 mSv on average through natural radiation with a typical range being 1-10 mSv (UNSCEAR, 2008, 2010; Chernobyl Forum, 2006). Low-level exposure for humans is then estimated to be a few mSv per year (Ibid). When expressing exposure in population terms, a person-Sievert or person-Rem may be used. This reflects the average dosage for one individual multiplied by the number of people exposed (Encyclopedia Britannica, undated).

To take the subject of radiation a step further, one needs to consider the half life of radionuclides (i.e. atoms exhibiting radioactivity). Radionuclides release radiation as they decay. This decay rate is commonly described in terms of half-lives, referring (as the name indicates) to the period required for half of a radionuclide to decay (UK Environmental Agency, Undated). Such rates vary widely among radionuclides. Caesium, for example, has a half-life of 30 years, whereas Plutonium-239/240 has a half life of 24,000 years (Ibid). Some radionuclides also begin with a short half-life, like Plutonium-241 (14 years), but transform in the decaying process to a radionuclide with a longer half-life, like Americium-241 (430 years) (Ibid).

In the context of nuclear power and the environment, Iodine-129 and 131 rank as important radioactive isotopes which are produced with the fissioning of uranium in nuclear reactors or with the fissioning of plutonium/uranium in nuclear weapons (EPA, 2012). These isotopes react readily with other chemicals and can disperse quickly in air and water (Ibid). Such isotopes may cause thyroid issues, and with long term exposure can lead to cancer (Ibid). Notably, I-239 has a half-life of 15.7 million years, whereas I-131 has a half-life of 8 days (Ibid; Tester et al, 2005, citing Parrington et al, 1996). In the event of a large release of radioactive iodine, stable iodine may be distributed (Ibid). Ingesting stable iodine is done to improve the probability that one's thyroid will absorb the stable form over the radioactive form during exposure (Ibid).

Waste Treatment

Waste treatment for nuclear plants has evolved for low, intermediate and high level waste which relates to varied risk and treatment (Sovacool and Valentine, 2012). Low level waste is understood to contain small amounts of radioactivity (Ibid). Intermediate waste carries a level of radioactivity which requires protective shielding during processing and/or transport (Ibid). High level waste can include reprocessing waste products and spent fuel as well as decommissioned reactors and uranium enrichment facilities (Ibid). Questions about how to manage nuclear waste present significant challenges across the technical, ecological, societal and economic spheres (Ibid). Deep geological repositories may serve as an option for long-term waste disposal, yet uncertainty remains in terms of the risks and implications for later generations.

Proliferation and Security

A concern that is uniquely characteristic of nuclear energy, among the class of energy options, is the potential for proliferation of fissile material, technology and/or knowledge to make nuclear weapons. This is underpinned by a fundamental worry that non-nuclear weapon states or radical groups might acquire tools and expertise to manufacture weapons of mass destruction.

To combat this, the Nuclear Non-Proliferation Treaty (NNPT) is designed to reduce the spread of such materials and know-how, to foster disarmament, and to encourage cooperation in peaceful applications of nuclear energy.[11] By some measures, the NNPT (in conjunction with the international non-proliferation regime) is largely successful. Nearly every state worldwide is a party, and there has been no net change in the number of states with nuclear weapons for twenty years (Bunn and Malin, 2009). However, theft and trafficking of nuclear materials remain a persistent reality. Between 1993 and 2011, confirmed incidents of illicit trafficking are reported to have numbered 2,164 (IAEA, 2012b).[12] Of these, sixteen incidents involved unauthorized possession of highly enriched uranium or plutonium, the fundamental ingredients for nuclear weapons (Ibid; Bunn and Malin, 2009).

Closely tied to proliferation concerns is the need to safeguard nuclear reactors and the fuel cycle against sabotage. Such destructive activity can have devastating consequences for not only people and the ecosystem in the vicinity of the targeted action, but can also affect those, for example, who are physically downwind or 'downstream' in the ecological chain (Bunn and Malin, 2009; Dreicer and Alexakhin; 1996; National Academy of Sciences, 2002). Here, technical and procedural safeguards can factor importantly as defensive measures in conjunction with culture, practices, and leadership highly attuned to safety and security; regulatory oversight; cooperation and resources; as well as information/communication channels.[13]

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[11] The Treaty currently has 190 signatories (UN Office for Disarmament Affairs, undated). It entered into force in 1970 and was extended indefinitely in 1995 (Ibid).

[12] It is highly unlikely that these numbers include all incidents.

[13] In addition to the NNPT, international conventions associated with nuclear security include the Convention on Physical Protection of Nuclear Material and Facilities, and

Finance and Economics

Nuclear energy projects entail large-scale investments, but once in operation such projects tend to have low and predictable fuel, operating and maintenance costs (IEA and NEA, 2010), assuming insurance is subsidized by the government or liability is limited. These cost considerations as well as the long, operating life-spans of nuclear power plants mean that high returns on investment are possible (NEA, 2007). With such cost dynamics, existing nuclear power plants in operation tend to be quite competitive, providing what is often the lowest-priced base-load power (WEC, 2010; discussion of base-load power is covered below with grid systems).

Another economic aspect of nuclear power is the front-loaded nature of such costs, which serves as an investment risk and financial challenge, particularly in liberalized markets (WEC, 2010). Construction costs are a major component of final, levelized costs of nuclear power (see Chapter 1, Appendix for levelized costs). This singular area of nuclear plant development is subject to many cost overruns (Schneider and Froggatt, 2012).

Yet another, economic dimension to nuclear technology is the cost tradeoff in back-end fuel cycle options. Storage of spent fuel awaiting more long-term disposal is considered to be much less costly than reprocessing (Bunn and Malin, 2009). Establishing a national repository is estimated to require multi-billion dollar costs and substantial

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the International Convention on the Suppression of Acts of Nuclear Terrorism (Bunn and Malin, 2009). These and other institutional attempts at oversight often lack specificity (Ibid).

technical demands (McCombie, 2009), although limited progress in this area leaves numbers open to speculation.

Markets, Expertise, and R&D

The nuclear energy market can be described as "low volume, but high value" (NEA, 2007). In line with this, limited equipment turnover occurs for technologies sold to large utilities or consortia of utilities, and with large initial investments (Ibid).

Nuclear power projects generally require long lead-times for what are often large and complex systems, necessitating the expertise of multiple disciplines. In the 31 countries which currently use nuclear energy, a certain level of sophistication is widely considered to be needed for relevant infrastructure and institutions (Ibid; Interviews, 2011). To address this, countries may turn to international vendors or international collaborations.

Specific to nuclear R&D, private nuclear equipment suppliers will generally focus on incremental upgrades, since the research is expensive and long-term (NEA, 2007). By contrast, governments will typically focus on more radical innovation, like the R&D underway with the Generation IV international partnership (Ibid; Generation IV Forum, undated).

The market is also subject to international agreements, like those related to export and waste transport (Ibid).[14] While these agreements are put in place to address concerns about the use of nuclear technology for military purposes and safety, they can have an unintended consequence of limiting commerce for civilian energy use.

Nuclear Power Plants within a Grid System

When considering nuclear power plants in the context of a grid system, it is important to distinguish between base-load and load-following power plants. Base-load power plants operate at maximum output generally all the time, except when taken off-line or have reductions in power for maintenance or servicing. These plants typically produce power at the lowest cost in power markets. Base-load power plants typically include fossil fuel plants, nuclear power, hydropower, geothermal energy, and biomass. In the case of nuclear energy, an added reason to maintain them constantly is that they require time to start up and shut down.

By contrast, load-following plants are those that are brought on-line as demand increases. The rule of thumb, here, is that plants with the lowest variable costs are brought on-line first. Natural gas and hydropower plants are typically used for load-following. Nuclear plants may also be used, as is done in France, but they are not employed for rapid variations (Interview, 2012).

[14] Such agreements include the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management, IAEA Safeguard Agreement, and Plutonium Disposition Agreement, among others,

C. ENERGY TRANSITION

The nuclear energy transition in France reflects one accomplished fundamentally by top-down intervention in actions of state agents with scaling of markets, technology, and expertise already in use. It was effectuated in a country which is home to 66 million people, has an economy of $2.2 trillion and is positioned highly among the class of 31 nuclear nations (IAEA-PRIS, 2012; CIA Factbook, 2012). France ranks at the top among nuclear states as far as the percentage of electricity derived from nuclear power is concerned with 77.7% in 2011 (IAEA-PRIS, 2012; for 2010 rankings, see Figure C1). France is also among the highest, second only to the United States, for the most nuclear reactors and nuclear power generation. It had 58 reactors producing 421,100 GWh on a net basis in 2011 (Ibid). Currently, France is the largest net exporter of nuclear power-backed electricity, producing roughly 4 billion dollars in annual revenue (WNA, 2012). It is also one of the largest, global reprocessors of nuclear fuel with roughly 17% of its electricity powered from recycled fuel (WNA, 2012; Sovacool and Valentine, 2012). Much of France's ascent to this highly nuclearized state occurred in the period since 1970, although its ties to atomic energy can be traced at least as far back as the late 19th century.

Historical Background

Nuclear scientist and former head of the American Nuclear Society Gail Marcus once said it is challenging to know where the story of nuclear fission originates (Marcus, 2010). The first known, natural occurrence of a fission reactor event was in the ore deposits of Gabon, Africa about 2 billion years ago (Ibid). Yet it took the science of the

20th century to recognize the event's significance (Ibid). While it is beyond the scope of this chapter to survey the full breadth of achievements in nuclear fission, for the purpose of understanding a national, nuclear energy transition, some recent developments are highlighted.

The element uranium was discovered in 1789 by a German chemist/apothecary, Martin Heinrich Klaproth (Ibid). Following this, a progression of discoveries and postulations set wheels in motion for France's adoption of this Promethean force. In 1896, French physicist Henri Becquerel discovered natural radioactivity, while studying the fluorescence of uranium salts (Ibid). French physicists Marie and Pierre Curie then discovered polonium and radium, with Marie Curie naming the phenomenon of radioactivity (Ibid).[15] During a subsequent period when many key findings relating to nuclear energy overlapped (Ibid; Goldschmidt, 1962), Irene and Frederic Joliot-Curie made a step forward with the creation of artificial radioactivity in 1934 (Ibid; Goldschmidt, 1962). This breakthrough by Marie and Pierre Curie's daughter and son-in-law made it possible to move from the testing of natural science to what some call 'controlled alchemy' (Marcus, 2010).

The succession of atomic energy developments continued as Italian Enrico Fermi and colleagues produced the first transformation by neutron bombardment, and Hungarian Leo Szilard put forward the first postulation on energy releases from neutron bombardment of nuclei (Ibid). In 1938, teams including Irene Curie-Joliot and Serbian

[15] Marie Curie was Polish by birth and lived in France.

Pavle Savic in France as well as Otto Hahn and Fritz Strassmann in Germany demonstrated the occurrence of fission (Ibid). By 1939, teams in the France, Germany and the United States were able to demonstrate neutron production during fission, conducting work to prove the possibility that nuclear chain reactions could be sustained (Ibid). Enrico Fermi's team at the University of Chicago produced the first self-sustaining nuclear reaction in 1942 (Sovacool, 2008; Marcus, 2012). Global attention then turned to atomic energy with the use of nuclear weapons by the United States in 1945.

Following the war, Prime Minister Charles de Gaulle of the French Provisional Government set out to modernize France, establishing the Commissariat a l'energie atomique (CEA) and Electricite de France (EDF) (Hecht, 2001). The CEA was charged as a newly formed public entity with studying nuclear reactor technology and managing development of the fuel supply needed for nuclear energy (Saumon and Puiseux, 1977). EDF was formed as a state-owned energy company from the nationalized power sector with the aim to provide reliable and abundant electricity for the French people (Hecht, 1991).

During the 1950s and 1960s, France rebuilt its infrastructure and economy (Lindberg, 1977; Price, 2005). To fuel the changes, indigenous coal reserves were limited and expensive, so hydropower was increased (Interview, 2011; Lindberg, 1977). In the process of expanding hydropower, EDF acquired key management experience in structural design, heavy equipment, and construction (Interview, 2011). EDF also jointly ran the French nuclear program with CEA, focusing on military and civilian energy applications (Hecht, 1991, 2001 and 2009; Schneider, 2008 and 2009). The Commission for the Production of Electricity from Nuclear Energy (La commission pour la Production d'Electricite d'Origine Nucleaire or PEON Commission) was also established to provide counsel on nuclear energy projects (Hecht, 2009; Interviews, 2011-2012). This body of roughly 20 government-appointed members included senior members of government, EDF, and CEA along with a number of other industrialists (Ibid). It would be positioned as an important link for French nuclear activities in the 1970s.

By the late 1960s, France's progress in nuclear technology showed strong promise for fuller expansion in energy applications as well as industrial export of nuclear equipment and services. Hydropower potential was considered to be already harnessed, while nuclear energy was viewed (at least by some) to be a gradual way forward (Interview, 2011). In international markets, competition among nuclear reactor designs gravitated toward the LWR, leading EDF to promote it. In short, EDF decision-makers wanted to build plants with large capacity which could lower investment costs (Linderg, 1977; Interviews 2011-2012). Based on technology performance to date, LWRs appeared well-suited for the aim (Ibid). Industrial export also looked to be more promising for the LWR design (Ibid).[16]

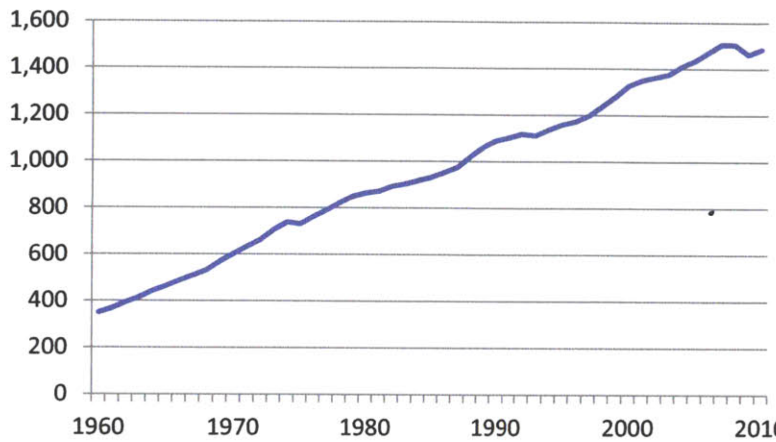
[16] Military incentive to use the NUGG diminished with the shift away from the A-bomb to the H-bomb, where demand for plutonium decreased (Lindberg, 1977; see fuel discussion in Section B).

What followed was a famous battle of the reactors (la guerre des filieres) led by state actors EDF and CEA, eventually ending with newly-inaugurated President Pompidou opting for the LWR path (Hecht, 2009; Interviews, 2011). In the next stage of France's nuclear program, the PWR line of LWR technology would be employed as the domestic nuclear industry mobilized and scaled (Nelkin and Pollak, 1980, Hecht, 2009).

France's Modern Nuclear Power Transition: 1970-the present

The period evaluated here began as France was riding a post-war wave dubbed "30 Glorieuses." This was an era of 30 years in which considerable industrial and socio-economic development occurred with increases in the standard of living, domestic consumption and population (Fourastie, 1979; Interview, 2012; Price, 2005). For the purposes of this study, this mattered since post-WWII rebuilding provided significant economic growth, based largely on energy-intensive industrialization (Figure C1; IAEA, 2011).

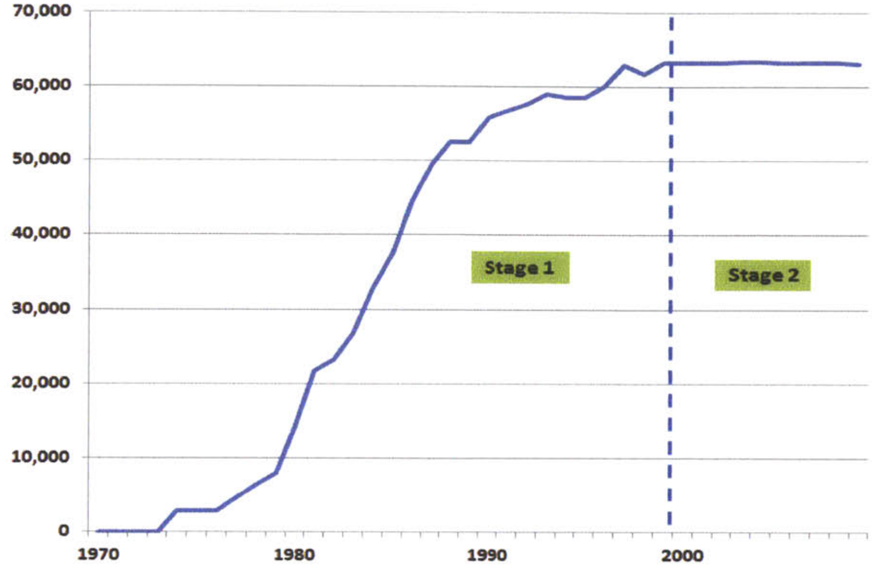
Figure C1: French GDP (Billion in constant US$, 2000)



Source: WDI data, 2012.

Similar to Denmark, France was heavily dependent on energy imports. In 1973, these imports accounted for more than 75% of energy consumed versus 38% in 1960 (Ibid). When the effects of the 1973 and 1979 oil shocks took hold, French petroleum import costs would increase by nearly a factor of 8 (UN Comtrade, 2012). Figure C2 illustrates the marked shift which occurred in French nuclear energy use from the 1970s to the present.

Figure C2: Stages of French Nuclear Power Development
(Net Cumulative Power Capacity from Nuclear Energy, MW)



Source: IEA data, 2012. Note: For 1970-1973, data exists but was not collected.

Stage 1: Accelerated Mobilization and Deployment (1970-1999)

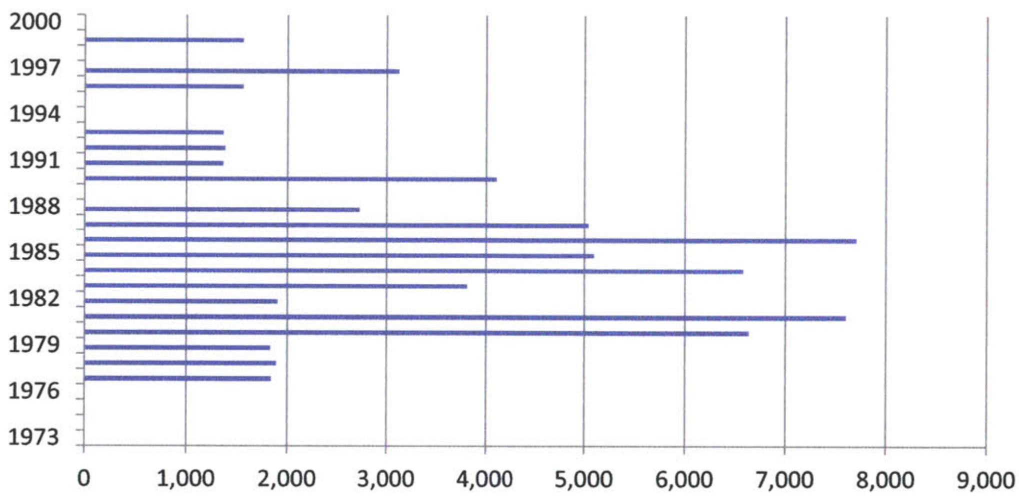
In some respects, the French nuclear energy transition was simple. It evolved and scaled from an existing base of technology, institutions, industry, and experts. The plan was set in motion by the French government, working with a network of state experts and minimal public engagement.

Fuller explanation emphasizes that the French government acting decisively in the aftermath of the first oil shock. Guided by aims of independence, a perceived limit to domestic energy options, strengths in science, and projections of substantial growth in energy demand,[17] the government understood the scale-up of its nuclear program as the logical way forward (Interviews, 2011-2012). The government of Prime Minister

[17] EDF estimated electricity demand of 1,000 TWh for the year 2000 to be covered by 80 PWRs and 20 FBRs, whereas the PEON Commission in 1973 projected demand of 750 TWh for the same year. The actual demand was 430 TWh (Grubler, 2009, citing G-M-T, 2000).

Messmer launched the nuclear program with an initial request for 6 pressurized water reactors (Ibid).[18] This set of 6 PWRs would be connected to the grid before the decade's end, and followed by 52 more (IAEA-PRIS, 2012, Figure C3).

Figure C3: Additions in Gross Electricity Capacity from New PWRs following the launch of the Messmer Plan *(MW)*



Source: IAEA-PRIS data, 2012.

In what could be characterized as the most comprehensive nuclear program to date, the French mobilization of its nuclear energy system was implemented principally by state agents EDF, Framatome, and CEA. EDF was the architect and manager of the nuclear power plants. Framatome was the primary manufacturer and developer, while the CEA managed nuclear R&D, oversaw the fuel cycle, and advised on nuclear technology. The crux of policy was embodied in direct actions of these state actors in the form of

[18] While the above version of events was regularly recounted in interviews, differences existed over how advanced the planning was for nuclear scale-up was in the early 1970s. One written source suggests that planning for a major scale-up of nuclear energy was already well underway in France before the events which precipitated the first oil shock (Golay et al, 1977).

deployment, R&D, etc. By the beginning of the 21st century, the program had a nuclear fleet of 58 PWRs (Table C1).[19]

Table C1: PWRs Installed in France Following the Launch of the Messmer Plan

Number of Units	Type	Capacity per Unit (approx)	Commissioned
34	PWR (CP0, CP1 and CP2)	900 MWe	1977-1987
20	PWR (P4 and P'4)	1,300 MWe	1984-1993
4	PWR (N4)	1,450 MWe	1996-2002

Source: IEA, 2004, IAEA, 2012a.

In tandem with the scale-up of the nuclear fleet within the power market was the mobilization of an industrial-sized, nuclear fuel cycle. This was accomplished by integrating and expanding existing capabilities, including reprocessing and fuel fabrication processes used for the nuclear defense program (IAEA, 2011; House, 2008).[20]

Considering the nuclear transition in terms of French society, the roll-out was launched publically on March 4, 1974, when Prime Minister Messmer - a decorated war hero,

[19] Two, experimental fast breeder reactors were also launched during the period of this study - the Phenix in 1973 and the Superphenix in 1986 (IAEA-PRIS, 2012).

[20] In 1976, for example, Cogema was established as a subsidiary of the CEA with the mandate to create an industrial group that would service all stages of the nuclear fuel cycle for civilian and military program needs (Schneider, 2008b). With its formation, Cogema was granted the industrial uranium fuel and reprocessing facilities previously overseen by the CEA (Ibid).

former governor of French colony Cameroun, and Minister of the Armies and of State charged with Overseas Territories - announced what has been called the Messmer Plan (Topcu, 2008). Based on what would later be seen as over-projections of French energy needs, Messmer indicated that 40 reactors would be ordered by 1980 (Surrey and Huggett, 1976). The announcement was, by many accounts, made without public consultation or the chance for substantive parliamentary debate (Interviews, 2011-2012; Nelkin and Pollak, 1980 and 1982).

According to one regularly-raised perspective, the French public broadly accepted the plan, seeing nuclear energy as the obvious and only solution to meet France's power needs (Interviews, 2011; Topcu, 2008). France's nuclear energy program had already been underway for decades and been proven at a smaller scale. The government also had to act quickly, given that fuel disruptions could create emergency-like conditions. Progress in industrialization and socio-economic development were also at risk. Moreover, the technical complexities of nuclear energy made public discussion unwieldy (Interviews, 2011-2012). Here, the government relied considerably on experts in EDF, Framatome, and CEA.

An alternative characterization, highlights areas of societal discontent and mobilization (Interviews, 2011-2012). Even before the Messmer Plan was announced, a reported 10,000-15,000 people had protested in 1971 against the siting of the Bugey 1 nuclear plant with demonstrations continuing across many cities (Surrey and Huggett, 1976; Nelkin and Pollak, 1982). Groups like Scientists for Information on Nuclear Energy

(GSIEN) began in short order to report on risk and radiation around French nuclear sites (Topcu, 2007 and 2008).[21] A petition was also launched in 1975 by 30 physicists working for the French Scientific Research Center (CNRS). This document was ultimately signed by several thousand researchers, challenging the 'all-nuclear' nature of the Messmer Plan, the lack of public information, and absence of independent control (Surrey and Huggett, 1976; Topcu, 2007 and 2008). *Alternatives to Nuclear*, published by scientists with the Institut Economique et Juridique de l'Energie et Grenoble, similarly criticized the Messmer Plan, but on the basis of sound economics (Surrey and Huggett, 1976).

Societal discontent was evident in other ways. Accounts point to a series of large-scale protests which occurred at nearly every new nuclear plant site, with a reported 175,000 people turning out over the course of ten demonstrations between 1975 and 1977 (Nelkin and Pollak, 1982; Kitschelt, 1986). At Creys-Malville alone, more than 100,000 people gathered in 1977 to oppose the Superphenix FBR (Locher, 2011). During this event, violence and one fatality occurred (Nelkin and Pollak, 1982). For those directly implementing the energy plan deployment, opposition was also encountered, such as when the home of the EDF president was bombed; EDF engineers' wives received small coffins by mail; and rockets were fired on the unfinished Superphenix plant (Interview, 2011; Besson, 2005; Marshall, 1982).

[21] The Committee Against Atomic Pollution, and Survive and Live, an ecological group formed by mathematicians, were two early groups measuring radiation (Topcu, 2008).

New global developments in the late 1970s brought additional concerns to the forefront. The nuclear meltdown in Unit 2 of the Three Mile Island plant precipitated another round of public questions on nuclear power safety. The second oil shock also aggravated an already weakened global economy with a heightened recession (see Appendix for timeline).

As the 1970s came to a close, political parties in France campaigned for parliamentary elections with the Socialists appealing to anti-nuclear concerns (Kitchelt, 1986; Locher, 2011). Once elected, the Socialists (under the leadership of President Mitterand) briefly interrupted, then continued the roll-out of the nuclear program, ultimately supporting an expansion of domestic and international nuclear plant sales (Ibid; Schneider, 2008b; Topcu, 2007; Collins, 2003; Marshall, 1982). At this time, a parliamentary discussion and vote on energy and domestic nuclear policy occurred for the first time in French history. Accounts suggest there was an inadequate procedure for informing citizens and lack of real debate with decisions already in place (Fagnani and Moatti, 1986, citing Bourjol and Lamer, 1982).

Explanations diverge on the reasoning for a temporary freeze in French nuclear energy deployment in the early 1980s. Some contend that economic growth was less than expected and an over-capacity of the electricity supply was already evident (IAEA, 2011; Interviews, 2011-2012). Others maintain that the Socialists reneged on their pre-election promises (Locher, 2011; Topcu, 2007) because of a deal struck with the trade union French Democratic Confederation of Labor (CFDT), marginalizing the anti-nuclear

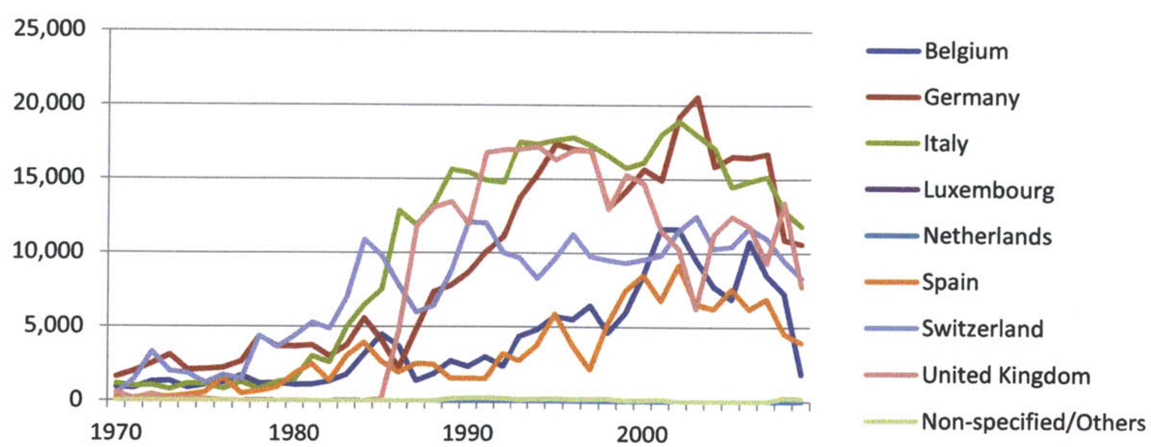
platform (Schneider, 2008b). In either case, the momentum of the national anti-nuclear protests receded, but local struggles, primarily against waste storage issues, would continue (Interview, 2012; Kitschelt, 1986; Topcu, 2007 and 2008).
The new decade was accompanied by other change in the French nuclear energy transition. The initial PWRs in the 1970s leveraged a Westinghouse license. However, with deepened experience, Framatome sought greater autonomy from its licensing agreement. Starting in 1982, the Westinghouse license was abandoned for French designs that would be used going forward.

The pivot in the nuclear program at the beginning of the 1980s was by no means satisfactory for everyone. In 1982, a blockade of 2,000 protesters at a proposed nuclear site in Carnet, France led to clashes between police and demonstrators with stones and Molotov cocktails (Collins, 1983). This was followed by farmers releasing bees to drive police and nuclear workers from a nuclear site (Ibid).

In April 1986, the Chernobyl nuclear accident in Reactor 4 raised questions again about the viability and safety of nuclear power. While the incident originated on foreign soil, radiation from the accident set off sensors in France, among other regions (Schneider, 2008b). In the week following the accident, the French Ministry of Agriculture issued a statement saying that the French territory was exempted from the radioactive fall-out, due to its distance from the accident (Ibid). The government destroyed one load of spinach, and French farmers disposed of what they viewed as tainted crops (Ibid; Greenwald, 1986, and Greenwald et al, 1986). Pierre Pellerin, the head of the French radiation protection agency (SCPRI) sent a notice, indicating that precautionary measures would be justified only at levels that were 10,000 or 100,000 times higher than those which were evident at the time (Schneider, 2008b). During this same period, independent laboratories were set up by scientists and new NGOs to measure radiation in areas around clusters of nuclear installations (Lehtonen, 2010a). The NGOs, ACRO in Normandy and CRIIRAD in Rhones-Alpes, were spearheaded by local residents in nuclear regions and aided by scientists and technicians (Topcu, 2008). Both groups mobilized to verify radiation levels (Ibid). Governmental response to Chernobyl would also be revisited in 2006, when Mr. Pellerin was indicted for aggravated deceit (Schneider, 2008b).

By 1986, 37 new PWRs and 1 FBR had been brought on-line (IAEA-PRIS, 2012). That same year, 70% of France's electricity was derived from nuclear energy compared to 4% in 1970 (IEA, 2012). France also began exporting increased amounts of electricity to neighboring countries (Figure C4).

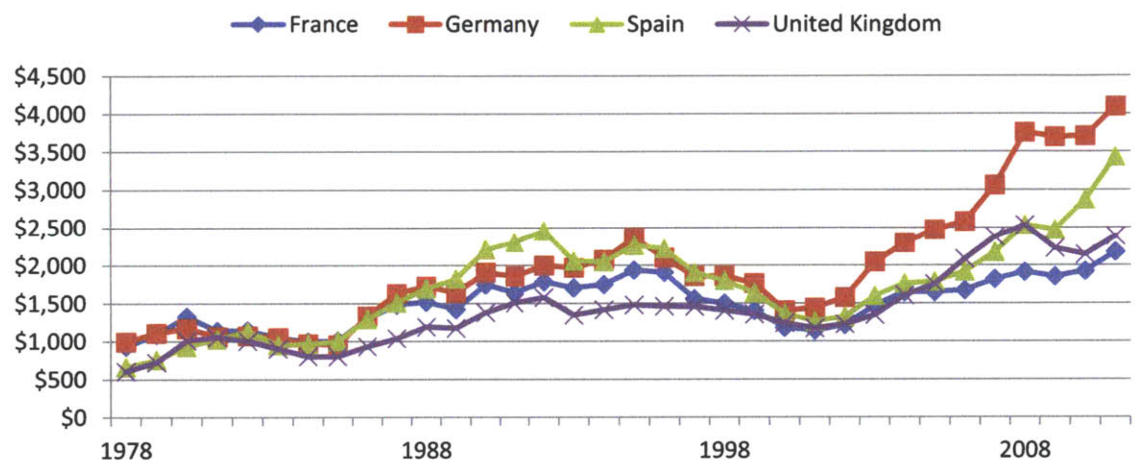
Figure C4: French Electricity Exports by Country (GWh)



Source: IEA data, 2012.

These exports of power were helped by the relatively inexpensive nature of French nuclear generation (based on regulated costs) compared to some of neighboring countries' electricity rates (IEA data, 2000, Figure C5).

Figure C5: Household Prices for Electricity (MWh) *($/TOE)*



Source: IEA data, 2012.

To address an over-capacity of power, France led in the practice of load-following with some of its 900 MWe PWRs for (WNA, 2012). This entailed adaptations to the reactors and grid management practices (see Innovations section).

As nuclear power production and the related volume of spent fuel increased, questions about nuclear waste management became more pronounced. Scientific experts considered irreversible disposal in geological repositories to be the only path, yet progress is this area was brought to a standstill in the late 1980s as protests heightened to a violent flashpoint (Lehtonen, 2010b; Interviews, 2011). Citizens questioned the meaning of being selected as "France's nuclear wastebasket," particularly when a rural area would be chosen and principally bring benefit to the urban demand centers (Lehtonen, 2010b, citing Barthe et al, 2010; Interviews, 2011). The government responded by appointing a parliamentary commission. At the request of the commission, Christian Bataille met with stakeholders, finding that reversibility was an important consideration (Interviews, 2011-2012; Lehtonen, 2010b, citing various).

The contentious discourse on nuclear waste led to the 1991 Waste Act. This postponed a national decision on waste management for 15 years (Lehtonen, 2010b). It also opened up the possibility of options, other than geological repositories (Ibid). A research program was launched to consider options including: (1) partitioning and transmutation,[22] (2) deep geological storage, and (3) interim storage (Ibid; IEA, 1996, 2000). Following the release of a key report in 1998 by the National Commission on Evaluation (CNE) and an international forum on reversibility, the government indicated that reversibility would be a central tenet for the long-term nuclear waste plan (Lehtonen, 2010b, citing Hoorelbeke, 2008 and Barthe, 2009).

Other changes were evident in the public treatment of information on nuclear energy (Topcu, 2008). Authorities began the practice of announcing technical issues with nuclear plants through on-line platforms (Ibid). Regulations were also tightened in La Hague, for instance, where NGO ACRO continued to measure radiation releases (Ibid). When a public controversy arose over possible links between leukemia and nuclear

[22] Partitioning and transmutation entail the separation of minor actinides and long-lived nuclides from high level waste, followed by the conversion of segregated elements into other nuclides to minimize the hazard and volume of high level waste (Knebel, 2009; Tsinghua University, 2010).

activities, the government responded by promoting public discussion (Ibid). This more open, information landscape was polarized later in 1990s by the emergence of the Nuclear Phase-out Network (Reseau Sortir du Nucleaire), an NGO born from the Superphenix FBR struggle (Ibid; Lehtonen, 2010b, citing Chateauraynaud et al, 2005).

On the technology front, an important joint venture was launched in 1992 in which Framatome and Siemens of Germany partnered to produce a next-in-class Generation III reactor with the European Pressurized Reactor (EPR). This collaboration would lead to a number of 'new builds' in the following decade.

Focusing on public engagement, a formal step was made with the passage of the Act of Michael Barnier in 1995. This Act, named after the European Commissioner for the Internal Market and Services, indicated that all infrastructural projects (nuclear ones in particular) required 'democratic debate' (Interview, 2012). In line with this, the National Commission on Public Debate (CNDP) was established, charged with guaranteeing a wide range of public perspectives. Pluralism of public perspectives would be considered on infrastructure projects, which stood to have substantial socio-economic or environmental impacts (Lehtonen, 2010a).

Safety testing re-emerged in the public forum in 1999, when a Level 2 event occurred at the French Le Blayais nuclear power plant. A combination of high tide and winds produced flooding which breached sea walls, resulting in a partial loss of the power supply (Interview, 2011; Mattei et al, 2001). Circuit failure for two units led to an automatic shut-down, with diesel generators that were based at a higher level starting up and maintaining power until the primary power supply was restored (Ibid). This multi-dimensional incident led to a large-scale reexamination of safeguards associated with multiple equipment failures (Mattei et al, 2001) -- a theme that would be revisited after the Fukushima events in 2011.

The latter part of Stage 1 ended with the 58th pressurized water reactor (and last N4 unit, Civaux 2) being connected to the grid in 1999 (IAEA-PRIS, 2012). The French government also sought to improve accountability and transparency related to safety (IEA, 2000). The Superphenix and fast neutron reactor development were shut down (Interview, 2011-2012) and a parliamentary debate on energy, including nuclear power, reaffirmed three fundamentals of French energy policy: namely, the security of supply, environmental respect, and appropriate attention to radioactive waste management (WNA, 2012).

Public discussions on nuclear energy acknowledged that natural gas had become increasingly competitive with technology developments in combined cycle gas turbines (IEA, 2000). However, natural gas did not hold an economic advantage over nuclear power (Ibid; WNA, 2012). Moreover, gas was accompanied by volatile pricing (Ibid). The IEA/NEA confirmed the competitiveness of nuclear energy for France relative to gas and coal (IEA, 2000, citing IEA 1998). This same analysis also found that France was the only IEA country where nuclear power was cheaper than gas as a base-load option (Ibid; see Cost Performance indicators).

The first energy transition stage ended with France's nuclear share of total electricity equaling 76% of total electricity in 1999 (Figure C6). In terms of nuclear generation, a nearly 70-fold increase was evident from 5,711 GWh in 1970 to 394,244 GWh in 1999 -- roughly a roughly 2-fold increase per year on average (Figure C7).

Figure C6: Share of Electricity from Nuclear Power

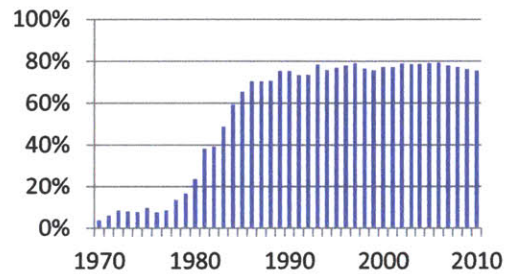
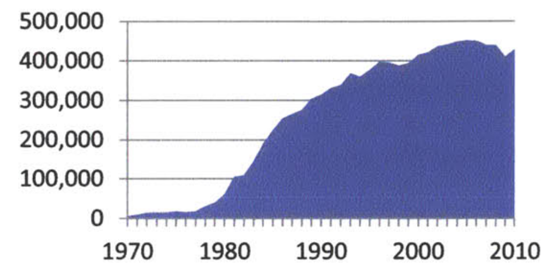


Figure C7: Nuclear Power Production *(GWh)*



Source: IEA data, 2012 for both.

Stage 2: New Dynamics in the Energy Path (2000-present)

The second stage of the French nuclear energy transition was characterized by regulatory review of a maturing nuclear fleet, plus a more expansive and diversified approach to energy policy. Spurred by EU directives, liberalization altered accountabilities and some activities of key players. However, the fundamental use of nuclear power in French electricity did not appear to change substantially. Formal public engagement was increasingly evident.

As the 21st century began, France had the second largest electricity market among IEA European countries, after Germany (IEA, 2000). France was also the largest electricity exporter among the IEA countries (Ibid).

Public ownership in the nuclear industry was reorganized in 2003 with consolidation in newly-formed AREVA encompassing Framatome, Cogema, ANP, Technicatome, AREVA T&D, and FCI (IEA, 2004). This brought nuclear reactor manufacturing, development and services together with the associated nuclear fuel cycle. That same year, the consortium of AREVA (Framatome ANP) and Siemens won a contract to build the 1st EPR project in Finland (Ibid). EDF would later lead the 1st domestic EPR project in France, once a decree officially accepted Flamanville as the EPR site in 2007 (Interview, 2012).

The existing nuclear fleet also began to undergo license renewals in order to extend operational life spans for plants to 50 years. The 900 MWe units all cleared their extension reviews in 2002 (WNA, 2012) and in 2006, the 1300 MWe series was also cleared, contingent upon minor modifications between 2005 and 2014 (Ibid). Later in the decade, EDF would indicate it was evaluating the prospect of 60 year life spans for the plants (Ibid).

A vulnerability of the French nuclear infrastructure was highlighted in the summer of 2003, as Europe experienced an extreme heat wave. Since the majority of nuclear plants were to be cooled with water from hotter than usual rivers, 19 French NPPs had to scale down operations. While energy shortages during the period cannot be wholly attributed to the French nuclear power scale-back, thousands of heat-related deaths nonetheless occurred that summer in France and Italy (Kenward, 2011).

During January of 2004, thousands of people gathered in Paris to oppose the development of new EPR projects (ABC News, 2004). Such EPRs would be the first, nuclear new builds in Western Europe since 1991 (Schneider and Froggatt, 2012). such opposition to nuclear energy would continue through 2012 with groups also challenging the transport of nuclear waste, safety, and seismicity issues, among other concerns in France (Interviews, 2011-2012).

Against a backdrop of continued protests was a series of public debates on energy led by the National Commission on Public Debates (*Commission nationale du débat public* or CNDP) in 2004-2005, followed by additional debates on the construction of the EPR, the siting of a high voltage line for the EPR, and waste management. While mentioned as a step toward transparency and participation (Interviews, 2011-2012), the debates, particularly those on the EPR and waste, have been criticized for being devoid of any impact on decision-making. According to some, the events were used to legitimize pre-determined decisions (Schneider, 2008b; Lehtonen, 2010a, citing Lhomme, 2006). Nonetheless, critics acknowledge that the CNDP was successful in resisting pressures from vested interests. The agency gained credibility for altering the rhetoric and for withstanding pressure on how the public discourse should be managed (Lehtonen, 2010b, citing GC 2006 and Chateauraynaud et al, 2005).

Specific to technology development, France joined and actively participated in the Generation IV International Forum for nuclear research development. This consortium brought 10 countries plus Euratom together in a high-level collaboration on advanced reactor designs (IEA, 2004; Gen IV Forum, 2012). Participants included Argentina, Canada, China, the EU, Japan, South Korea, Russia, South Africa, Switzerland, the

United Kingdom and the United States in addition to France (Gen IV Forum, 2012). Related to this, Cadarache, France was officially selected as the site for demonstration of the International Thermonuclear Experimental Reactor (ITER) and international nuclear fusion research and engineering project (NEA, 2009).

In 2005, an energy law was passed, setting targets for energy efficiency and renewables, as well as a target to reduce CO_2 emissions by 75% by 2050 from the base year of 1990 (IEA, 2010). In terms of energy fuels, the law codified targets for RETs equaling 10% of total primary energy and 21% of gross electricity by 2010 (IEA, 2010). The law also emphasized aims related to energy security, diversification of energy imports, and energy savings, leaving nuclear choices open-ended (IEA, 2010; Interview, 2012).

After a review of findings on waste management research and public debate, key laws were passed in 2006, on safety, transparency and management of radioactive waste. With these laws, continued research was mandated for long-term geological disposal, transmutation and interim storage (Lehtonen, 2010b) with reversible geological disposal retained as the reference point (Ibid, citing ANDRA, 2010). Additional clarification was provided, distinguishing recoverability from reversibility. The former corresponds to the technical capacity to recover waste, whereas the latter refers to prospect of altering and/or reversing decisions (Lehtonen, 2010b).

The following year, initiatives were launched to strengthen nuclear education (Interview, 2012; Schneider 2008). The aim in part is to replenish the expert pool and support export of nuclear technology (Interview, 2012).

Public discourse also continued with roundtable of discussions on the environmental issues (*Grenelle de l'Environnmente)* that included the national government, unions, NGOs, employers, civil society and local authorities (IEA, 2010). These discussions resulted in the development of an environmental program with institutional reforms (see MEEDDM) plus a package of new energy policies tied to renewables, emissions, and labeling, etc.

In 2008, France adopted an Energy and Climate package together with the other EU-27, setting targets for GHG reductions, efficiency and RETs (IEA, 2010).[23] French climate plans were also introduced and updated to bolster actions in transport and buildings as well as to include new measures that were the outcome of the public, *Grenelle de l'Environnment* discussions (IEA, 2010). With the passage of Grenelle I and II Acts in 2009-2010, the French energy sector was encouraged to diversify with a variety of renewables through feed-in tariffs, tendering schemes, income tax credits, and tax exemptions (IEA, 2010). This concerted approach, if effectuated, would prove to be a major change in the French government's fostering of energy development.

[23] According to this, France must meet a 14% reduction target in GHGs in sectors outside of the EU-Emission Trading System and increase its share of RETs in total final energy consumption to 23% by 2020 with a 10% target in the transport sector (IEA, 2010). France's own previously set targets exceeded those of its EU targets (Ibid).

With respect to the power sector, the playing field was altered during the decade as liberalization took effect. A wholesale electricity market was put in place in 2001 (IEA, 2010).[24] An energy regulatory body, the Commission de regulation de l'energie (CRE), was also set up with devolved oversight powers to ensure smooth and efficient management of practices related to competition (laws Feb 10 2000 and Jan 3 2003) (IEA, 2010). Tied to this, EDF was converted to a limited liability company in 2004 (Act of August 9, 2004) with the law stipulating that the French State would continue to hold at least 70% of the capital and voting rights (IAEA, 2010). [25] Over the course of the decade, accounting and legal unbundling of the transmission and distribution system operators for the grid was also completed, yet ownership of the system operators remained much in the sphere of EDF. As of 2007, liberalization of the French electricity market was completed. Nonetheless, the power sector remained quite concentrated with EDF accounting for 88% of the supply (IEA, 2010).

In conjunction with other shifts, the government also implemented institutional reform related to energy and the environment. It created the new Ministry of Ecology, Energy, Sustainable Development and the Sea (MEEDDM) with a goal of more integrated and coherent address of these areas (IEA, 2010). In 2008, the Agence France Nucleaire International (AFNI) was created under the CEA to foster the establishment of nuclear

[24] This is based on EU Directives 96/92/EC and 2003/54/EC.

[25] EDF, France's main electricity company and manager of its nuclear power facilities, was a vertically integrated power company and the largest power company in Europe (IEA, 2000). Since 1969, government oversight of EDF was done via multi-year agreements (*contrats de plan, contrats d'enterprise*) (Ibid). With each consecutive agreement, EDF gained greater autonomy, based on its attainment of performance goals, like price reductions (Ibid).

programs in other countries (WNA, 2012). That same year, a high level Nuclear Policy Council was set up by presidential decree, comprised of the president, prime minister, cabinet secretaries, head of CEA, and heads of the military (WNA, 2012). This body has been active in managing nuclear energy policy and the nuclear industry.

More recently, a number of additional developments hold relevance. EPRs under construction by AREVA and EDF have encountered substantial time and cost overruns (Schneider and Froggatt, 2012). In 2008, construction on the French EPR was halted by the French regulatory authority ASN to tighten up documentation and quality standards associated with concrete, welding and steel framing (Grubler 2010, citing Greenpeace). The relationship between AREVA and EDF became strained, as these leading French companies competed abroad (Interviews, 2011). The Nuclear Policy Council directed AREVA and EDF to develop a strategic partnership for domestic needs (Ibid).

In March 2011, an earthquake and tsunami-induced nuclear accident at the Fukushima Daichi plant in Japan brought nuclear power again into the global limelight, as one of the leading nuclear nations wrestled with fall-out from its Level 7 accident. In contrast to the Chernobyl aftermath, the French government reported fall-out measurements (Interview, 2012). The Prime Minister also directed the French nuclear safety authority, Autortite de Surete Nucleaire (ASN), to complete a safety audit of French nuclear facility resilience beyond existing 'dimensioning principles' (Pouget-Abadie, 2012). Two days later the European Council asked the European Nuclear Safety Regulators' Group and the European Commission to commence stress testing of all reactors in the European

Union (Ibid). Shortly thereafter, a number of European countries, including Germany, initiated phase-outs of domestic reactors (WEC, 2012). This affected the regional power market with some looking to French nuclear energy to provide more base-load power (Interviews, 2011). Tests of French nuclear facilities were completed, gauging threshold effects relative to threat scenarios that included a core meltdown and substantial environmental discharge (Pouget-Abadie, 2012). French reactors were also tested for the possibility of all reactors at one site being affected by conditions over a longer period of time (Ibid). Later that year, the French agency on nuclear radiation and safety, Institut de Radioprotection et de Surete Nucleaire (IRSN), released a 500 page report indicating that each French nuclear power facility needed an additional safety layer for cooling and power functionality, as with an independent and externally positioned diesel generator (Boselli, 2011). The head of the IRSN also noted that Bugey, Fessenheim and Civaux plants could be strengthened against seismicity, and Fessenheim, Chinon, Craus, Saint-Laurent, and Tricastin plants should be augmented for flooding (Ibid). Protests honoring the accidents at Fukushima and Chernobyl focused on closing the oldest nuclear plants (Bouvier, 2011).

In early 2012, the French Cour des Comptes, a court of audit akin to the United States General Accounting Office, reported on the French nuclear industry and fleet (2012). Among findings related to cost and strategy, the court indicated that planned replacement of the current French fleet could not be adequately accomplished based on the assumed time and cost factors (Ibid). Lifetime extensions of the nuclear fleet and/or a new energy strategy would be needed (Ibid).

As for the new EPRs being built, the Flamanville 3 project is estimated by the Cour des Comptes to be roughly 3 times the originally-planned 2003 construction and power generating costs (Ibid). The Finnish project, for which AREVA is a partner, is approximately 5 years behind schedule and 100-120% over budget (Schneider and Froggatt, 2012). EDF also indicates that its 2 unit EPR project in the UK is more than 4 times the 2003 estimated cost, implying electricity production costs (depending on the rate of return) that are 2-3 times the current average base-load price in the United Kingdom (Ibid).[26]

Finally, political change is evident with newly-elected President Hollande, who: reversed an EPR new build decision that would have been sited at Penly; announced the closure of the Fessenhiem plant (a site of protest over seismicity and safety); and supported a goal to shift the French energy mix from 75% nuclear-based electricity to 50% (Interview, 2012). Public talks on nuclear energy are planned for the Fall of 2012 (Ibid).

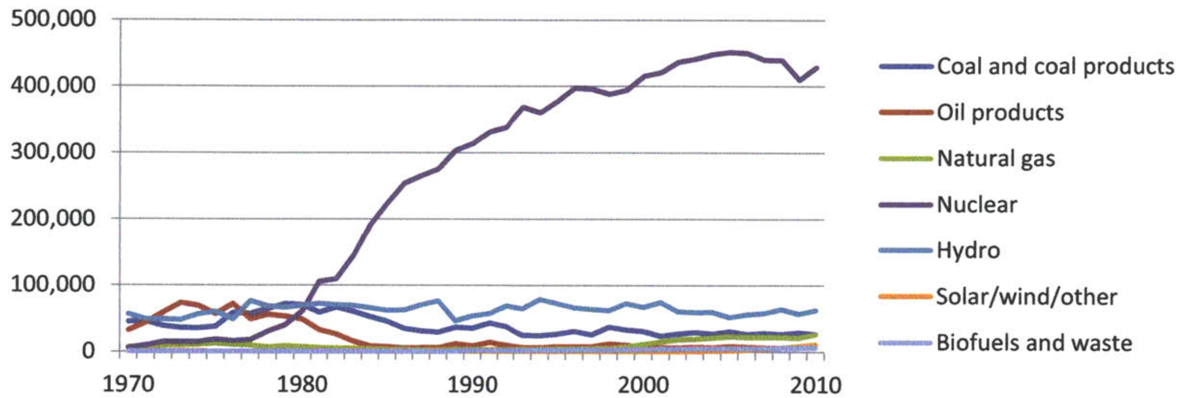
Recap

The French power trajectory underwent striking change over the last four decades with oil use declining and trends in other traditional power generation fuels being flat, as nuclear power ascended to dominate the mix (Figure C8). The share of nuclear power rose from 4% of total electricity in 1970 to 70% in just the first sixteen years, finishing out the period of this study at 78%. The targeted policies which enabled this transition were often not explicit, but rather directly embodied in actions of state agents as they

[26] The UK government is considering using a contract for difference to assure ample profit for investors (Schneider and Froggatt, 2012).

scaled the program from existing nuclear capabilities. Currently, France's total generating capacity as of the end of 2011 was 126 GWe with nuclear power comprising 63 GWe (WNA, 2012).

Figure C8: French Power Generation by Fuel Type *(GWh)*



Source: IEA data , 2012.

D. INNOVATIONS and ADAPTATIONS

Key innovations and adaptations are discussed under the following groupings:

- **Reactor technology:** Standardization; design changes; shifts for load-following and MOX use;

- **Fuel cycle:** Development of a full fuel cycle at an industrial level which could handle domestic and international clients.

Reactor Technology

Design standardization is a hallmark of the French nuclear program, as it brought substantial uniformity (a form of adaptation) across the 900, 1300 and 1450 reactor series (WNA, 2012). In addition to fostering economies of scale, standardization also enabled gains in learning and transfer of knowledge across operators and reactor models (Interviews, 2012; see also the Costs section). This uniformity provided greater predictability in the scale-up and utilization of the nuclear fleet, yet also brought inherent risk if a generic, technical problem were to appear across a model series. Combined with management practices, this standardization imposed structure on user innovation. EDF head Marcel Boiteux is said to have instructed engineers at EDF and Framatome to make notes of improvements (breakthrough or otherwise) for the next series of reactor, but no changes were to be made at that time (Interview, 2011; Grubler, 2012, citing Boiteux, 2009).

Among other major adaptations and innovations were those associated with reactor design. The early-staged shift to the PWR reactor technology, based on the Westinghouse license, was accompanied by an increased need for enriched uranium and adjustments in the fuel cycle. Use of the Westinghouse design; however, was short-lived, as a desire for greater technological/industrial autonomy and problems with the Westinghouse design compelled Framatome to turn to French PWR designs.[27]

[27] The Westinghouse design utilized steam generators which had persistent issues with corrosion, thereby increasing the number of tube ruptures (Woo and Lu, 1981, citing Berges and Vignes, 1981; Interview, 2012). Among the improvements were new plate material with corrosion-resistant steel, modified arrangements of tubing and support

In the time since 1970, incremental safety developments were also regularly introduced as retrofits and new model functionality, however more radical physical shifts were evident in size and efficiency. French reactors grew from 900 MWe to 1300 MWe and eventually 1450 MWe. The EPR currently being built for Flamanville 3 is 1650 MWe (IAEA-PRIS, 2012). With these plant size shifts, one also finds a design evolution from 3 loops in the 900 MWe design to 4 loops in 1300 and 1450 MWe, presumably to allow for gains in overall efficiency in line with the 2nd law of thermodynamics (Interview, 2012; WNA, 2012).[28]

Two additional, highly important changes in reactor technology occurred with load-following and the use of MOX fuel. Load-following with French nuclear power plants was introduced to account for over-capacity of supply. To accomplish this, less efficient and less absorptive 'grey' control rods were added to the fuel assembly of some PWRs of the 900 MWe design to adjust the reactor and to control the power distribution, thereby allowing sustained variation in power output (WNA, 2012; Interview, 2012). By adopting load-following (and sometimes powering down reactors on weekends), the capacity factor of French PWRs at 77.3% is lower than global standards of about 90% (new nuclear reactors); nonetheless, availability is nearly 84% and rising (WNA, 2012; von

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plates (triangular mesh, water channels along the tubes, etc), and increased thermo-hydraulic performance leading to improved efficiency (Interview, 2012).

As a consequence of the shift to French designs, component fabrication shops in Chalon, Le Creusot, Maubege, and Belfort improved manufacture time (Interviews, 2012).

[28] Modifications like these were shared with Westinghouse to be eventually applied in American plants (Interview, 2012; WNA, 2012).

Hippel, 2010). Roughly 20 of the 900 MWe PWRs were also adapted to operate with an enriched uranium-MOX blend that included 30% MOX (CEA, 2010). For this, plant modifications required more control rod clusters (Interview, 2012).

Development of an Industrial-scale Fuel cycle

The development of a full, industrial-scale fuel cycle represented a major step in scaling the existing French energy transition. Underpinning this were integrated planning and process redesign with institutional revisions (Interview, 2012).

The CEA managed the earliest aspects of the fuel cycle based on the agency's 1946 mandate to develop all aspects of atomic energy, including civilian and military applications (IAEA, 2011a). Over time, including the period studied here, the CEA's functions and oversight evolved (Ibid; Interviews, 2011). Industrial production elements of CEA's fuel cycle activities were largely spun off to form Cogema, which was later merged with Framatome and other entities to create AREVA.

Today, divisions within the AREVA Group work with public agency ANDRA (L'Agence nationale pour la gestion des dechets radioactifs) and other partners to manage the full nuclear fuel cycle. The AREVA Group is an industrial and commercial leader in fuel cycle phases, engineering and services (IAEA, 2010) which include prospecting and mining (AREVA NC); conversion (Comurhex); enrichment (Eurodif, Georges Besse II); fuel fabrication (AREVA NP for uranium oxide and AREVA NC/Melox for MOX); plus reprocessing and packaging (AREVA NC) (Ibid). Radioactive waste management and disposal are managed by ANDRA (Ibid).

Power Market and Grid System Changes

Similar to the Danish wind energy transition, the liberalization of the power market in France had some bearing on the studied energy system transition, although use of nuclear generation did not change significantly. State-owned energy company EDF unbundled some of its functions, spinning off grid oversight to the Transmission System Operator Reseau de Transport d'Electricite (RTE).[29] Competition with liberalization brought the opportunity for consumers to purchase power from multiple providers, meaning that EDF no longer held a full monopoly over the portfolio of options and new rationale would factor in investment and planning (see Power Markets – Vertically Integrated and Competitive Regimes, Chapter 5, Appendix).

Finally, in conjunction with the load-following technology adaptations mentioned above are the altered practices in the power market and grid management. Load-following with nuclear power, as discussed in Section B, is unusual, yet over-capacity of installed power warranted changes, beginning in the 1980s.

Sectoral Contributions

Estimated weighting of sectoral contributions in the innovations and adaptations mentioned above is laid out in Table D3. Influences were defined, based on insight from

[29] RTE was formed as an internal division of EDF in 2000 with independent finance, management and accounts (RTE, 2012).

interview feedback, historical reporting, and case analysis with the strength of weighting indicated by the number of squares per category.

Table D3: Sectoral Contributions to Innovation/Adaptations

Innovation/Adaptation	National Government	Industry	Civil Society	Other (Academia, NGOs, etc)
Reactor Technology				
• Design change: NUGG to PWR	■■■	■■■		*
• Design change: Westinghouse to French	■■	■■■		■■
• Size	■	■■■		■
• Fleet level standardization	■	■■■		
• Safety	■■■	■■	■	■
• Load Following	■	■■■		■
• MOX Fueling	■■	■■		■
Fuel cycle	■■■	■■■		■■
Grid and power market development	■■	■■■		■■

*Note: EDF and Framatome/Cogema/AREVA are state-owned, although now only partly, so are included under Industry and National Government. CEA is a public R&D and oversight agency, which oversees the fuel cycle and is part owner of Framatome/Areva, so is classed with National Government, Industry and Other. Local governments and the EU authorities are classed with Other. *The CEA's involvement with the shift from NUGG to PWR was to oppose the change.*

From this summary of rough estimates, a number of patterns and differences in sectoral contributions are evident. Government and industry are actively involved in all areas, by implementing the change directly or indirectly through SOEs. Civil society's role is limited to safety developments (mostly indirect in form), yet their input is not deemed passive, since some constituencies were quite vocal and exemplifying activism. The EU (included with Other) impacted the power market, principally through liberalization. The CEA (included with Industry, Government, and Other) has been centrally involved in almost all developments with rare exception.

E. KEY DRIVERS and BARRIERS

The accelerated and robust deployment of nuclear energy in France's energy transition can be credited in part to institutional, policy and political aspects of French society. Power (of the societal influence form, rather than electric generation) is concentrated in select bodies. Moreover, France has strong engineering and science traditions. Opportunity for public dissent in decision-making was also limited during much of the early period of this study. Such features are explored next.

Drivers

- Desire to reduce oil import dependence and deleterious impacts on the balance of payments/self-sufficiency
- Concentrated power with limited public participation
- Centralized planning
- Robust policy backed by strong political support
- Independence and technological leadership
- Control of the nuclear fuel supply

Desire to reduce oil import dependence and deleterious impacts on the balance of payments/self-sufficiency

The Messmer Plan was launched in the wake of the first oil shock and has been actively supported or at a minimum passively allowed to continue under 15 prime ministers and 5 presidents. This was driven at least in part by a fundamental aim to reduce oil imports and their deleterious effects on the balance of payments for a country which had undergone major, post-war industrialization. While the change in the energy mix and import dependence is covered in Section G and the Appendix, the following elaborates on the import aspects of the balance of payments.

Figures E1 and E2 illustrate import costs of petroleum in nominal dollars for France and as a share of all French import costs. While both indicators are affected by influences beyond the scope of this study, they do reveal a number of relevant insights. First, import costs of petroleum were mostly flat for much of the 1990s, then sharply increased in the last decade, not unlike flux in international oil pricing (see Chapter 1, Figure E2). Second, petroleum's share of total French import costs was high during the period of the two oil shocks, yet has been substantially lower since then. This underscores that while oil import costs remain a consideration for the balance of payments, the nuclear program has allowed France to minimize its vulnerability to oil price flux in the power sector.

Figure E1: Import Costs of Petroleum *(Billion, nominal $)*

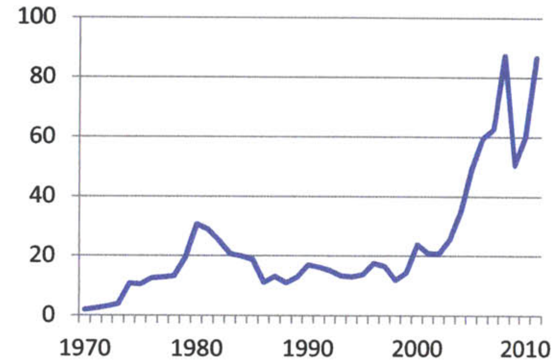
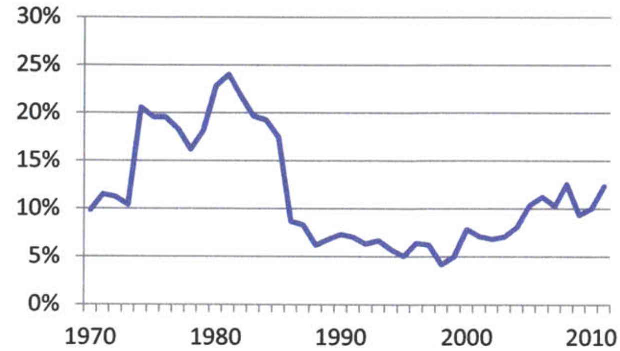


Figure E2: Petroleum as % Total Import Costs *(Trade Balance)*



Source: UN Comtrade data, SITC Rev 1, Petroleum and Petroleum Products data, 2012 for both.

Concentrated decision-making with limited public participation

Historically, political and economic bases of power in France have been highly centralized by comparison to most OECD countries (IEA, 2010). In line with this, many assessing the French nuclear energy trajectory will point to the limited number of institutions and actors making decisions behind the rapid scale-up of the French nuclear program (Finon and Starpoli, 2001; Jasper, 1992, Grubler, 2010). For the period of this study, the government worked with CEA, EDF, Framatome/Cogema/AREVA, and others like Alsthom to deploy the nuclear program with advice from PEON in the early years and the Nuclear Policy Council in more recent years. Bridging these insulated institutions was a small circle of expert managers, often drawn from the Corp des Mines and Corps des Ponts (Grubler, 2010; Schneider, 2008 and 2009; Interviews 2011-2012). As government administrations changed, the core of this network and its shared vision remained largely intact (Ibid; Vendrys, 1986). This network and PEON

Commission both appear to have been central nodes for policy development, implementation and continuity (Interviews, 2011-2012).

Essential to this governance approach was an institutional structure which allowed powerful ministries to act, yet not be directly answerable to the public (Fagnani and Moatti, 1986; Kitschelt, 1986; Golay et al, 1977; Interviews, 2011-2012). During the earlier period of this study in particular, the public had very limited access or opportunity for review of governmental actions and information (Interviews, 2011-2012; Golay et al, 1977). This appears to be based on the principle that government utilizes expert counsel on the public's behalf, avoiding the situation of subjecting the public to needless concern (Ibid). As a consequence of this style of governance, public knowledge on technical aspects of the nuclear program relating to safety and environmental protection was limited (Golay et al 1977).

French law, as codified and treated in the courts, did not allow significant societal redress of grievance with government decisions. Golay et al (1977) note that French law focuses on objectives, rather than the detailed mechanics of how to attain aims, allowing an implementer to determine an 'optimal approach' (Ibid). If a citizen challenges actions done in the execution of nuclear energy policy, the French courts will focus on whether the letter of the law was met (i.e. objective attained) and not the technical appropriateness of the challenged action (Ibid).

Centralized Approach and Planning

Closely tied to the above decision-making is French planning which has been characterized as highly centralized (Ibid). For the period 1946-2006, the Commissariat General du Plan (CGP) was a principal institution behind public investment strategy with its use of 5 year plans that distilled objectives to guide social and economic development (Lindberg, 1977). One example of this structured prioritization was with the development of France's TGV high speed rail for public transportation.

In more recent years, the 5 year plans have ceased to exist and the CGP has since been replaced by the Strategic Analysis Center which serves in a similar capacity (Interview, 2012). Yet old planning practices continue in a new form. Today, the government requires Pluri-annual Investment Plans (PPIs) by companies like EDF and AREVA to evaluate investment options, ensuring they are in line with desired future development goals (IEA, 2010).[30] For electricity (and by extension nuclear energy), if the goals of energy security, for example, are not met, the government may open a tendering auction (Ibid).

Robust Energy Policy Backed by Political Support

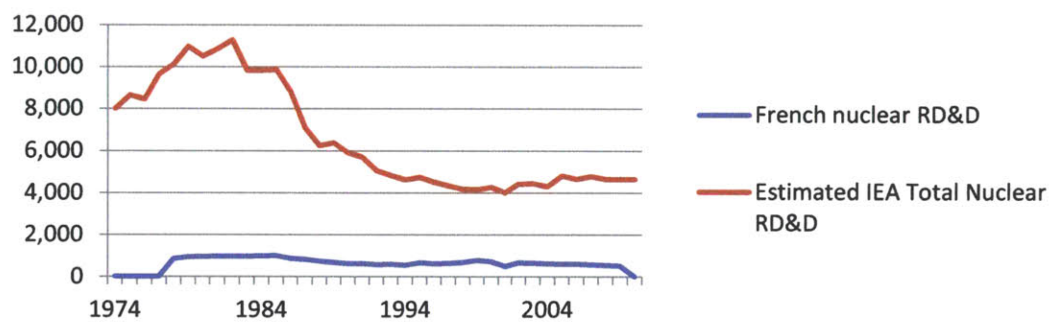
Nuclear energy policy in France has been robust and principally embodied in the actions of state agents, supported by strong political backing throughout the period studied (Interviews, 2011-2012). While the Socialist Party in the late 1970s questioned

[30] This is currently to be done by all EU countries, as indicated in the EU Electricity Directive.

the nuclear plan during the campaign season, party members under Socialist President Mitterand ultimately backed the nuclear program's continuation. The Socialist-Green parties of the late 1990s also challenged aspects of the program, which led to the closure of the Super Phenix FBR in 1997/1998. These mid-course pivots were comparatively small relative to the overall program roll-out.

For added insight on policy support, the energy technology RD&D budget highlights the focus of spending. Figure E3 shows the continuity of French RD&D expenditure on nuclear energy relative to the flux in overall IEA country expenditure for the same.[31]

Figure E3: French RD&D (2010 $ million, ppp)



Source: IEA data, 2012. Data for France 1974-1978 exists but was not collected.

Considered from a different angle, Figure E4 shows shifts in the amount of spending on nuclear RD&D in France across the period, with the greatest amount of expenditure not surprisingly in the earlier stage of the study. The figure also shows that, despite shifts, nuclear energy received the lion share of funding.

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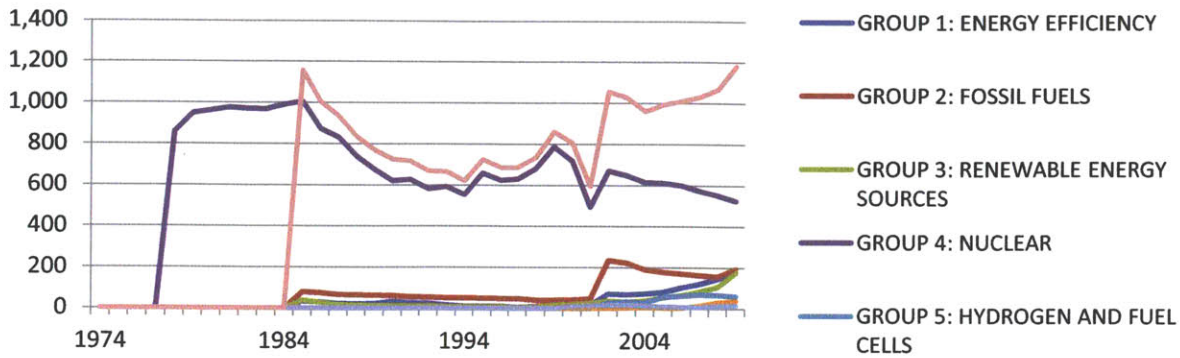
[31] It is possible that some RD&D expenditure for the civilian nuclear program could be covered by the military program, akin to a subsidy, although no evidence was seen over the course of this study.

Figure E4: RD&D Budget *($ 2010 million, ppp)*



Source: IEA data, 2012. Note: Missing values for some fuels. Data exist, but were not collected.

Today, signs of discontinuity are afoot in French energy policy with newly-elected President Hollande. Early indications show that he prefers energy diversification, yet what remains to be seen are the concrete steps to be taken, particularly during and after the Fall 2012 public consultation on energy.

When discussing French nuclear energy policy, it is also worth underscoring that overlap between the military and civilian programs existed throughout the period of nuclear development in France (Schneider, 2008; Hecht, 2009). A primary nexus is within the CEA, which was initially created to oversee both lines of development and which continues in both areas today (Schneider, 2009; CEA, 2012). Analysis of the military intricacies of French nuclear power goes well beyond the bounds of this research; however it is useful to note that the senior level decision-making for the programs often accounted for the duality of purpose. Choices, for instance, on reprocessing of spent fuel, use of FBRs, and production of plutonium intersected both civilian and military domains. To ignore the military dimension would deny synergies, spillover effects, and feedback loops. Limitations from international agreements on exports and transport of nuclear fuel also mattered. In more concrete terms, the creation of the industrial fuel cycle under Cogema gained an early advantage by absorbing infrastructure, material, personnel and related expertise from the military program. This subject area was limited by information availability and access to some of the primary political decision-makers from the period, and merits further exploration.

National Independence and Leadership in Science and Technology

Independence and leadership in science and technology were two additional drivers regularly raised to explain French nuclear development. Independence can be traced at least as far back as to the rebuilding of the French society and economy following WWII (Price, 2005, Hecht, 2009; Interviews, 2011-2012). Moreover, experiences with the Suez Crisis and with President de Gaulle's choice to remove France from NATO are emblematic of a national independence streak which motivated the adoption of nuclear energy and shielded the industry from some criticism (Interviews, 2011-2012; Sovacool and Valentine, 2012).

Complementing the interest in independence was France's traditional leadership in science and technology. France's deep historical roots in physics provided important cultural traction for the nuclear program. Breakthroughs by French scientists Becquerel, the Curie-Joliot family of scientists, and Goldschmidt, among others, were familiar reference points for the public and political decision-makers' viewing contemporary nuclear scientists. The postwar French nuclear program was also considered by many to be a source of national pride and a pursuit mirroring that of the Manhattan Project or Space Race (Interviews, 2011-2012; Hecht, 2009). If these elements are considered holistically with the co-benefits of the expert network described above, they provide insight on why some in French society were willing to defer to such experts (Sovacool and Valentine, 2012) and why a technologically complex, yet more indigenous energy course may have been seen as reasonable.

Control of the Nuclear Fuel Supply

(This is a driver and barrier. See discussion under Barriers.)

Barriers

- Public opposition
- Financing
- Expert pool
- Control of the nuclear fuel supply

Public Opposition

Public perceptions about nuclear energy and, in particular, opposition to it is a phenomenon which continues to be studied (Chausssade, 1990; Hecht, 2001; Kitschelt, 1986; Nelkin and Pollak, 1980 and 1982; Topcu, 2007 and 2008). In France, opposition was evident at least as early as the 1970s, and was at times violent, but never appeared to critically challenge the viability of the nuclear program (Sovacool and Valentine, 2012). Interestingly, the presence of radical opposition during different periods may also have had the unintended consequence of insulating the program even further (Ibid).

Opposition took numerous forms. It was driven by residents in communities where nuclear facilities were being sited; domestic and international environmental NGOs (Greenpeace); NGOs opposed nuclear power (Reseau Sortir du Nucleaire); and scientists who sought to improve information on the nuclear power choices and their implications, or challenged what was publically disseminated (GSIEN, WISE-Paris). Residents in areas with existing nuclear cycle units also formed partnerships with scientists and laboratories to collect, analyze and disseminate local knowledge (ACRO and CRIIRAD).

Reasons for opposition were manifold. In simple terms, concerns over safety were tied principally to radiation and the risk of accidents. There was multi-layered discontent over the process, transparency, regional equity, uncertainty with respect to waste, and the extent of local engagement in decision-making (Interviews, 2011-2012). Some also challenged the centralized nature of the nuclear system (Ibid). Trust in decision-makers was also brought into question after high-level errors, such as that involving incorrect notification following the Chernobyl accident (Ibid; Schneider, 2008).

According to some who support the nuclear program, reporting by the press contributed (incorrectly at times) to heightened opposition by providing facts without adequate context (Interviews, 2011-2012). The presence of international protesters, particularly from Germany, was also seen as fueling domestic discontent (Ibid).

In line with these concerns were the limited channels for decision-making review and redress of grievances for French citizens. Here, opposition utilized extra-parliamentary means in public protests and counter-expert reporting.

Financing

The way the nuclear program was financed is a subject still coming to light. However, a number of sources indicated financing challenges. According to some interviewees, the civilian nuclear energy program was not subsidized (2011). For companies, like EDF, which carried substantial program-related debt and began to see a profit in 1985 from sales of electricity exports (Jeffery, 1986), self-financing was an impediment (Interviews, 2011; Boulin and Boiteux, 2000). According to one source, public regulations also did not allow EDF to raise its electricity tariff in order to balance its accounts (Jeffrey, 1986, citing Business Week), which would have complicated the economic sustainability of the nuclear program roll-out. EDF secured external (i.e. non-state) funds; however some point out that the company's favorable status as a state-backed enterprise would have improved the conditions of the loans (Interviews, 2011-2012).

Returning to the issue of subsidies, it is reasonable to say that the military program was paid by the state and, by extension, its tax payers. Overlapping gains in research, expertise and perhaps equipment between the defense and civilian nuclear programs likely reduced some of the financing challenges for both.

Expert pool

Another challenge for the nuclear development, according to interviewees, was the development of a sustained pool of experts. While France's schools are well-known for training top science and technology experts, and the nuclear program was deemed the equivalent of the Space Race, the contemporary pool of available nuclear experts has at different points been seen as thinning (Interviews, 2011-2012; Schneider, 2008). In line with this, the French government has recently instituted a program to educate French and international students in nuclear energy (Ibid).

Control of the Nuclear Fuel Supply

Finally, control of the nuclear fuel supply served as both a barrier to and driver of the nuclear transition. Until the late 1970s, autonomy and flexibility in nuclear power decision-making was encumbered by incomplete control over the nuclear fuel cycle. Restrictions on and control of fissile material sourced from the United States and Canada, for example, drove France to develop its own enrichment technology (Interview, 2012). Until the Eurodif plant came online in the late 1970s, enriched uranium was acquired from the United States or USSR (Lindberg, 1977).

F. CLASSIFYING CHANGE

When considering the source and direction of the French nuclear energy transition over the period studied, it can be described as top-down and managed by public actors. The government and state agents, namely CEA, EDF and AREVA, drove all major adaptations with some indirect influence by civil society's undisputed interest in safety. The means of implementation was direct deployment. Over time, the government (including SOEs) informed the public on some areas related to nuclear energy, but the level of adequacy remains subject to debate.

Turning to the pace and intensity of traditional fuel displacement with nuclear energy: Stage 1 was rapid and substantial, with nuclear energy rising from a 4% share to 76% of total electricity; Stage 2 more or less maintained levels already achieved, starting and ending around 77% with a slight rise to 79% mid-decade (Figure C6). If the pace of change is gauged instead with installed nuclear capacity: Stage 1 was similarly robust, increasing from 1974 (the beginning point where data is collected by OECD/IEA) to 1999 by a factor of 22; Stage 2 declined marginally (OECD/IEA, 2012).

In terms of technology change, radical and incremental changes are evident. Among radical changes, were the development of the industrial level fuel cycle, and adoption of load-following practices. In terms of incremental changes, adaptations in safety features were significant.

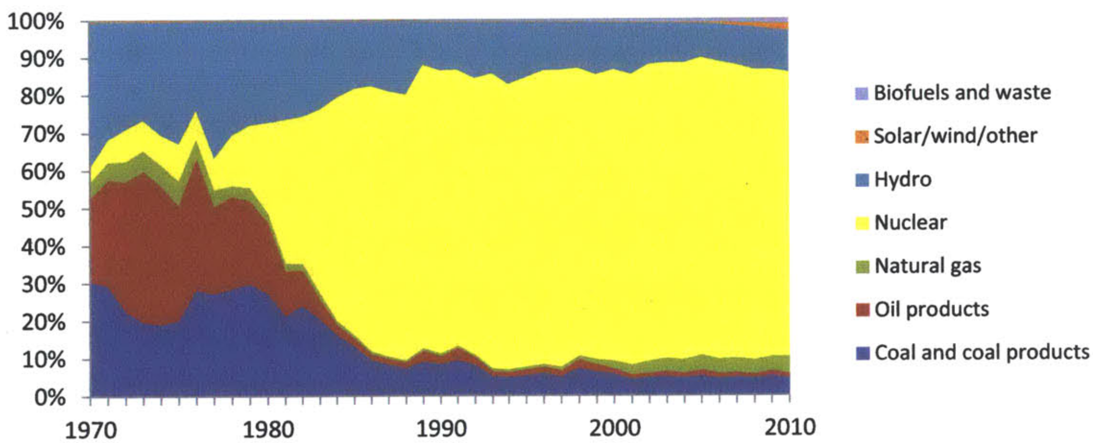
G. CHANGE INDICATORS

The French nuclear energy transition is gauged next for shifts in energy mix, costs, societal acceptance and industrial development. Additional indicators are included in the Appendix.

Energy Mix

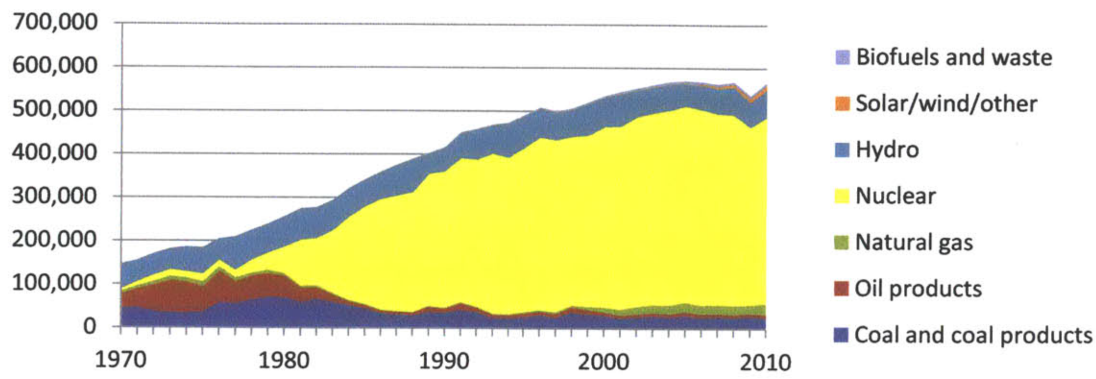
The share of electricity derived from nuclear power moved substantially from 4% to 78% between 1970 and 2011. This shift is shown in relative and absolute terms in Figures G1 and G2.

Figure G1: Fuels Used in Electricity Production in France *(Relative Shares)*



Source: IEA data, 2012.

Figure G2: Fuels used in French Electricity Production *(GWh)*



Source: IEA data, 2012.

Costs

Until recent years, reliable cost information about the French nuclear program was not available in the open literature or in published reports. In the late 1990s, a number of studies were commissioned for Prime Minister Jospin and Parliament on the French energy program (Bataille and Gailley, 1999; Charpin et al, 2000; Girard et al 2000; see Grubler, 2010 for discussion of these). Some over-arching conclusions were that France should maintain its course with fuel reprocessing (Grubler, 2010, citing Charpin et al, 2000) and that nuclear energy was competitive for France (Bataille and Gailley, 1999).[32]

In 2011-2012, the French Cour des Comptes assessed the costs and state of the French nuclear program (2012). Its findings, published in January 2012, estimated the

[32] The Bataille and Galley analysis of the country's energy program for the French National Assembly found French nuclear energy to be economically competitive for the national energy mix (1999). Cost of electricity analysis by the IEA around the same period (1998) found that new nuclear energy, based on discount rates of 5 and 10% and prevailing market assumptions, was in fact competitive for France.

total cost of the French program for facility costs of 58 PWR reactors, excluding the Superphenix FBR, were €121 billion (€2010) ($154 billion).[33]

The report also found that initial construction costs (including engineering) had nearly doubled between 1978 and 2000, whereas the average cost for the plants across the 58 PWRs was roughly 17% more than the original cost of the first plant (Table G1).

Table G1: Change in Project Costs/MW

Time (Plant)	Reactor Cost/MW
- 1978 (Fessenheim)	€1.07 million$_{2010}$/MW
- 2000 (Chooz 1 and 2)	€2.06 million $_{2010}$/MW
- 2002 (Civaux)	€1.37 million $_{2010}$/MW
- Average for 58 plants	€1.25 million $_{2010}$/MW

Source: Corps des Comptes, 2012.

This increase is due principally to safety requirements, according to the report (Cour des Comptes, 2012).

Analysis of construction times for nuclear plants provides another way to gauge costs. A study of France and the United States by Mark Cooper reveals there has been a marked increase in the time to completion for nuclear plants in both countries, a finding

[33] Within this, €96 billion ($122 billion) equates to (1) the construction costs of initial investment between 1973 and 2002 (i.e. overnight costs) of €83 billion ($106 billion), plus (2) interest during construction, estimated at €13 billion ($17 billion) (Cour des Comptes, 2012).

A 2010 Euro-Dollar conversion rate of .002466 was used (IRS, 2012).

that is consistent with other studies, like MIT's *Future of Nuclear Power* (2003 and 2009).

Arnulf Grubler (2009 and 2010) and Komanoff (2010) also identified a cost escalation in the French PWRs, although at a higher level than that found in the Cour des Compte study.[34]

When viewed together, the cost increases reveal a limit to basic learning curve expectations that costs should decrease with cumulative increases in an energy technology over time (Grubler, 2010). With such negative learning, Grubler points to a theoretical framework raised by Amory Lovins (1986) and referencing the Bupp-Derian-Komanoff-Taylor hypothesis (B-D-K-T) which says that technology scale-up can lead to greater system complexity (i.e. load following, fuel cycle, etc), and thereby lead to cost increases (Ibid).

On related fronts, estimates for dismantling the nuclear plants indicate a cost of €18.4 billion $_{2010}$, ($24 billion) (Cour des Comptes, 2012). Yet these estimates come with caveats that experience in the field reveals a tendency for numbers to increase as operations take shape. Subsequent to the release of the Cour des Comptes report, the nuclear financing committee (CNEF), comprised of members of parliament and experts, estimated that the current €34 billion ($41 billion) in assets that are set aside by nuclear

[34] This distinction can be partly attributed to the differences in data. Grubler and Komanoff's costs assessments (as well as Cooper's) are based primarily on Grubler's data which was developed with educated estimates from the late 1990s governmental studies (2010).

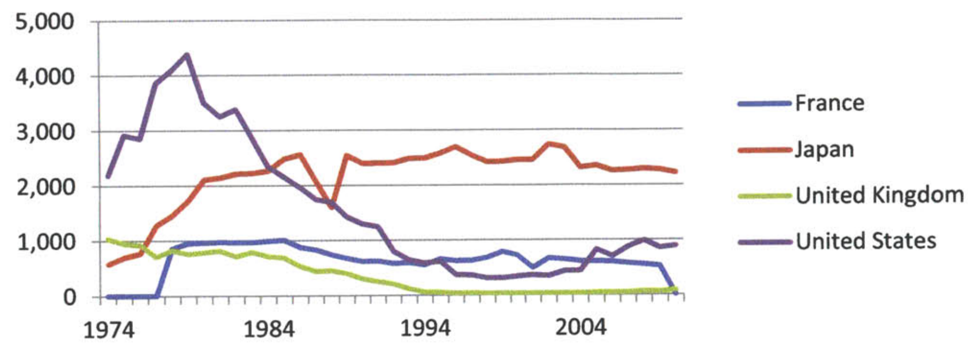
companies (namely EDF and AREVA) for dismantling would need to be augmented to meet longer term needs (Reuters, 2012).

Estimates for long-term radioactive waste management point to a cost of €36 billion $_{2010}$ or \$46 billion, twice that of an original estimate which is questioned by producers (Cour des Comptes, 2012).

Based on cost expectations, the Cour des Comptes report closed by indicating that lifetime extensions for the nuclear reactors or new energy policy would be needed in order to maintain the existing nuclear program. It bears re-emphasizing that the relationship between the military and civilian programs likely allowed cost gains or losses that are not fully captured here.

If one were to compare energy research, development and demonstration spending on nuclear technology for France, the United Kingdom, United States and Japan (some nuclear OECD countries) from 1974 to 2010, one would find that France spent significantly less than the United States or Japan on nuclear energy for much if not all of the period (Figure G3). This suggests that France's low cost nuclear-backed electricity was not exacted at an extraordinary expense in relative terms (or was well managed across civilian and defense purposes), so may arguably be deemed sustainable.

Figure G3: Comparative RD&D on Nuclear *(Millions $ 2010, ppp)*



Source: IEA data, 2012. Note: Data for France 1974-1977, and 2010 exists, but was not collected.

Turning next to the question of who paid, the answer is complicated by the mixed information that is available. EDF managers maintain that EDF was not subsidized (Interviews, 2011) and that it carried significant debt during the program roll-out, not earning a profit until the mid 1980s. According to one report, half of France's nuclear program cost, excluding construction cost interest, was self-financed by EDF; 8% was invested and discounted by the state in 1981; and the remaining 42% was covered by commercial loans (WNA, 2012). As note earlier, there are some indications that the commercial loans EDF secured may have been on highly favorable terms, given its governmentally-backed position (Interviews, 2011-2012; Grubler, 2010). At some point, there were also indications that some debt was written off, but the details require further study (Interviews, 2011-2012). Essentially, rate payers (i.e. electricity consumers) covered a credible portion of the costs for the nuclear energy program. Yet tax payers also paid, through indirect costs of SOEs and expenditure for military uses which impacted the civilian program.

Societal Acceptance

French society's view of nuclear energy as a centerpiece of its national energy system and military program is a complex subject with many angles. As discussed earlier, some viewed the energy path as one of 'no choice'. France had exploited much of its known hydropower potential and alternative options, like coal or gas, would have maintained heavy reliance on imports. Scaling nuclear power with domestically built power plants and a full fuel cycle, tapped indigenous technical strength, but did not entirely bring energy independence. France imports uranium today for its nuclear fuel stock. In the earlier years of French nuclear development, France had a domestic stock of uranium resources, but also developed a supply chain primarily with its former colonies (Schneider, 2009; NEA, 2006). The security of the fuel stock has remained an important rationale underlying demonstration with FBRs, introduction of processing and MOX fuel, etc. Interestingly, renewables, such as wind power, do not appear to have been considered extensively, making today's robust installation of 6 GW of wind power and plans to diversify with RETs all the more interesting (IEA, 2010).

Gabrielle Hecht's study of the French nuclear development, principally covering decades leading up to 1970, highlighted the importance of national identity and excellence in science and technology as values shaping societal acceptance of nuclear power(2009). Georges Vendryes, former Adviser to the CEA Administrator General, offered a different view:

> ...(for) forty years the big decisions concerning the development of the French nuclear program are taken by a very restricted group of personalities that occupy key positions in the government or in the top administration of EDF, CEA and the few companies involved in the program. The approach remains unchanged in

> spite of the change of ministers thanks to the permanence of these personalities that occupy the same position generally for some ten years (IAEA Bulletin,1986).

This latter view echoes earlier points on centralized decision-making. In short, there are those who are actively in favor of nuclear, others actively opposed, and some who remain undecided or passive about its effectuation (Interviews, 2011-2012). This dynamic of split views tests society's social contract in line with philosophy of Rousseau, Hobbes, and Locke.

In France's case, it appears that governments are cognizant of the sensitivities in societal acceptance. Since the 1990s, there are some signs of a deliberative turn (Lehtonen, 2010a) with greater participation in public debates on controversial policy points and public reporting on waste management and costs/issues of the nuclear program. The 2006 indictment of a French official for misleading the public in the aftermath of the Chernobyl accident is another sign (symbolic or otherwise) acknowledging the value of the government-society contract.

Industrial Development

France is the largest net exporter of electricity with power generation being its fourth largest export (WNA, 2012). France has some of the lowest cost electricity in Europe, due in part to plant extensions, and perhaps gains from dual purpose civilian-military use (Schneider, 2008b; 2009; Interviews, 2011-2012).

In the past decade, France exported up to 70 billion kWh (70 TWh) on an annual net basis (WNA, 2012). The IEA has encouraged France to seriously consider expanding its export role in the context of the EU electricity market going forward (IEA, 2010). The fact that EU states, like Germany, have nuclear phase-out plans underway (WEC, 2012; Schneider and Froggatt, 2012) presents new opportunities for increasing France's electricity exports at the EU level.

France is actively engaged in developing reactor technology (i.e. EPR, Gen IV) and in installing plants (Finland EPR). Its decision to build an EPR in Flamanville ties closely to plans and a decision by 2015 to build a series of 40 EPRs in France (WNA, 2012).

Nuclear reactors, fuel products as well as services are also major exports (WNA, 2012). The 900 MWe reactor design, for example, had been sold in a variety of export markets, including 2 units for Iran (1977), 3 units in Belgium (Tihange and Doel) 2 units for South Africa (Koeberg), 2 units for South Korea (Ulchin), 4 units for China (Daya Bay and Long Ao) (WNA, 2012; Schneider, 2009).

EDF manages the largest nuclear fleet in the world (Morningstar, 2012). Overall, it holds 75 GWe of nuclear power plants. Its businesses span the globe (Ibid) with its primary focus in the French and European electricity sectors (Ibid). RTE, a subsidiary of EDF, oversees the French transmission network which is the largest in the EU (Ibid). Its concentrated risk exposure to French power regulation and politics is a consideration for investors (Ibid).

AREVA, in conjunction with ANDRA, oversees the fuel cycle which serves the domestic market and global clients. Its world market shares are about 20-30% uranium mining, uranium conversion, and uranium enrichment; and 30-35% for low enriched uranium fuel fabrication (Schneider, 2009). It is also the largest builder of nuclear power reactors, holding a 20-25% share of the global market for nuclear power plant construction and services (Ibid). Additionally, AREVA dominates the back-end fuel cycle with 70-75% of the spent fuel reprocessing and 65-70% of the MOX fabrication (Ibid). It is 90% state-owned (AREVA, 2012).

Specific to France's power sector, if surplus power continues to be exported at exceptionally low prices or is used inefficiently to power domestic heating (rather than using district heating, when available) (Schneider, 2008), then real opportunity exists to improve sustainable practices. Moreover, if peak demand can swing widely with winter temperature drops and nuclear technology remains less flexible, then energy diversification (possibly with demand side management) should be fully explored. According to one report, today's plants are being installed with load-following as a built-in feature (WNA, 2012).

Looking to EDF and AREVA, the two industrial actors, one finds companies that are experiencing adaptation challenges tied to international competition; nonetheless they appear to be well-positioned (Interviews, 2011-2012). A major question remains on global interest in nuclear energy, following the Fukushima accident and announced phase-out plans.

Additional Points on the Environment and Safety

In terms of the environment and safety, numerous questions and uncertainties remain. Among the many are those linked to water availability, seismicity, decommissioning and waste, radiation and risk of proliferation.

Specific to water, the brown-outs of 2003 revealed a vulnerability in the heavy reliance on nuclear power. Additional study is needed, specific to the local conditions in this area (Interviews, 2012). For seismicity, the Fukushima accident and subsequent stress testing in France revealed weaknesses in some domestic plants which are in the process of being addressed. Naturally, fortification against unknown risk for natural disaster is no guarantee of full protection against accidents. With respect to decommissioning, 13 reactors are currently being decommissioned with what are reported as well-developed plans (WNA, 2012). It is beyond the scope of this study to assess this in the context of sustainability; nonetheless, advances must be made in securing disposal sites. Currently, there is also no management solution in place for recycling spent MOX and enriched recycled uranium (Cour des Comptes, 2012).

With respect to radiation, a recent report by the European Commission found that average routine discharges from the French La Hague site result in a collective dose of 3600 person-Sievarts (Schneider and Marignac, 2008). Based on a risk factor gauge of the International Commission on Radiological Protection, this dose is associated with roughly 180 fatalities per year (Ibid, citing ICRP, 1991). Extrapolating further with the remaining, planned operating life of the facilities, the long-term collective dose would equal 65,000 person–Sieverts, or 3,250 theoretical fatalities due to cancer (Ibid). This compares to 40 person–Sieverts in the global collective dose from the 1979 TMI accident and 600,000 for Chernobyl (Ibid, referencing Bennet, 1995; UNSCEAR, 1993 and UK HPOA/CEPN, 2006). Clearly, this area merits closer scrutiny.

Finally, France's stockpile of separated plutonium, planned initially as a fuel for FBRs, but also understood as a proliferation risk, has increased. EDF's stockpile grew from < 1 ton in 1988 to 51 ton in 2005 (Schneider and Marignac, 2008). Plutonium is being used in MOX fuel for up to 20 licensed 900 MWe PWRs, although, EDF is using less MOX than allowed (Ibid).

When combined with continued questions of social acceptance and rising costs, response to these deeply rooted concerns may hold the key for sustaining the nuclear energy use.

H. CONCLUSION

French nuclear development since 1970 is a 'classic case' of a government deploying an energy transition. Placing essentially full political backing behind nuclear energy development, the French government and public actors mobilized to effectuate a robust and rapid shift, by drawing upon an existing transition. Traditions in science and technology, a system of governance with limited public engagement, apt policy support and the experience of strong public actors, all factored.

Unique attributes of nuclear technology were somewhat defining of this case. Costs increases, rather than decreases, were seen with new projects. Technological complexity, standardization, and the centralized nature to projects also lent to a different kind of learning and innovation – rather than user innovations driving incremental change, mostly formal R&D, institutionalized partnerships, and accidents that shaped learning and change.

Ultimately, after a small group of decision-makers in France rolled out an extraordinary energy transition, the extent to which nuclear energy will sustain in its prominent position remains open to question. The strength of nuclear continuity in France may well ride on the heels of societal acceptance, sunk costs, or vested interests in a playing field where 'new' options are now seen.

APPENDIX

Timeline of French Energy Transition

1945

- CEA is founded

1946

- France nationalizes its electricity sector and creates EDF

1957

- Euratom Treaty is signed

1960s

- Debate between EDF and CEA occurs over which nuclear reactor technology to commercially use going forward. It ends in the late 1960s with LWRs being chosen.

1972

- Committee against Atomic Pollution is established in The Hague
- Survivre et Vivre reveals cracks in nuclear waste storage barrels in Saclay
- Eurodif partnership (Belgium, France, Iran, Italy and Spain) chooses diffusion process for its Tricastin enrichment plant that will be based in France.

1973

- 1st Oil Shock

1974

- PM Messmer announces what became known as the Messmer Plan

1975

- Approximately 30 CNRS physicists expressed opposition to the Messmer Plan with a petition that became known as Appeal of 400

1976

- CEA creates COGEMA

1977

- First criticality of Fessenheim 1. Order of Superphenix, 1200 MWe Fast Breeder

- Part of the European consortium of utilities (EDF = 51%), EDF began the building the world's only commercial fast breeder Superphenix, using enriched Ur and Pl capable of generating 12,000 MW, at Creys-Melville on the Rhone River (27 billion French Francs)

- Major demonstrations take place near the SuperPhenix site, one demonstrator was killed

1978

- Creation of EURODIF, a subsidiary of now AREVA, to exploit the French Gaseous Diffusion technology (with Italy, Spain Belgium and later Iran)

Late 1970s

- Fading of the national, anti-nuclear movement

1979

- 2nd oil shock, Iranian Revolution
- TMI nuclear accident
- China Syndrome movie released
- Tricastin enrichment begins

1981-1995

- Major change in French politics - the Socialist party gets absolute majority, but little change in the nuclear program which now supplies 50% of the French electricity

1983

- High inflation and economic problems lead Mitterand to reverse economic reform to follow fiscal and spending restraint.

Mid 1980s

- EDF begins sales and services in international market, especially French-speaking Africa and in 1985 China

1985

- Framatome, under the leadership of Jean Claude Leny, sets out to diversify

1986

- Chernobyl nuclear accident
- A subsea power cable connecting France and England is completed (done for contingencies, but becomes an export route)

1987

- France's 1st severity scale developed by *Conseil Supérieur de la Sûreté et de l'Information Nucléaires* (French Higher Council for Nuclear Safety and Information)/CSSIN

- Brundtland Report is released

Late 1980s

- Riots related to waste management

1988

- EDF plants operate at average load factor of 61% (W Germany 74%, Switzerland 84%, Finland 92%)

- EU internal burden-sharing agreement on GHG reductions, June 17

1989

- Framatome and Siemens form a subsidiary to design which leads to the EPR design

1990s

- Autorité de sûreté nucléaire (ASN – French Nuclear Safety Authority) plays a key role in the establishment of the INES2 International Nuclear and Radiological Event Classification scale published by the IAEA

1990

- All waste exploratory digging/processes stopped. Issue turned over to Parliament which appoints Christian Bataille

1995

- Strikes protesting a move toward free market reform.

- France ends its nuclear weapons tests 1960-1995

1996

- France ceased production of weapons grade fissile materials

- The EU decides to open electricity markets to competition

1997

- Kyoto Protocol is adopted
- The Jospin government stops Superphénix

1998

- SPD-Green coalition in Germany decides a nuclear phase-out (accelerated in 2011)

1999

- Level 2 Event at La Blayais

2001

- The last uranium mine closes in France

2003

- Order for the first EPR by TVO (Olkilioto 3)

2004

- Public debates begin
- Government and EDF announce Flamanville as the next EPR site

2006

- Construction begins on Flamanville EPR and at Tricastin for a new enrichment facility (George Besse II) to replace Eurodif in operation since 1978
- Laws passed on waste management, transparency and security in the nuclear field

2007

- EDF begins construction on its first domestic EPR, Flamanville-3

2008

- Flamanville-3 construction is suspended by the French nuclear safety authorities to correct measures
- EDF and AREVA sign a framework agreement for reprocessing all spent fuel, excluding MOX, through 2040

2010

- Reprocessing – La Hague handles 1,050 t spent fuel/year from EDF (vs. 850 previously) and Melox will generate 120 tons of MOX fuel for domestic NPPs

2011

- Fukushima nuclear accident
- German Chancellor Merkel announces an immediate shutdown of 8/17 reactors; Legislation is passed in the Bundestag (7/31/11), commencing a phase-out of nuclear energy
- French Prime Minister asks the Cour des Comptes to prepare, as part of its assignment to assist the French Government (now defined under Article L.132-4-1 of the Financial Courts Code) a report on the costs of the nuclear power sector" to be submitted before 31 January 2012

2012

- 2 small fires contained at water-cooled Penly PWR reactor; release of smoke spurred auto shut-down, no environmental effects reported
- Shutdown of EURODIF and commissioning of Georges Besse 2, the new centrifuge enrichment plant.
- Newly elected President François Hollande announces the shut-down of Fessenheim

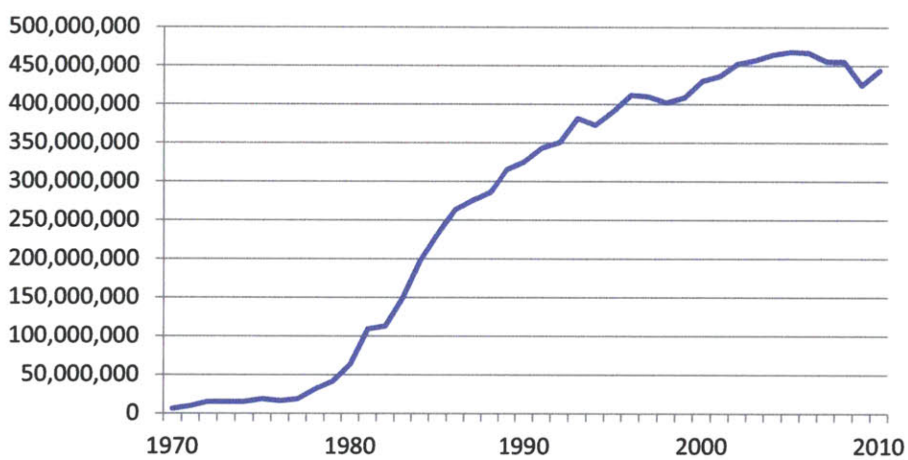
2016

- Flamanville EPR plant planned to be completed.

Estimated Carbon Savings

Gauging the carbon savings of nuclear power adoption, the coefficient calculation is applied with a number of assumptions. First, nuclear energy is presumed to displace coal on a direct content basis. Based on this methodology, 10.9 billion t CO_2 were cumulatively avoided by integrating nuclear power into the total primary energy supply in the period between 1970 and 2010 *(Herold, 2003)*. This equals 273.7 million t CO_2 on average per year. Figure A1 illustrates the estimated CO_2 emissions avoided through substitution of nuclear energy for oil.

Figure A1: Avoided CO_2 Emissions *(t CO_2)*



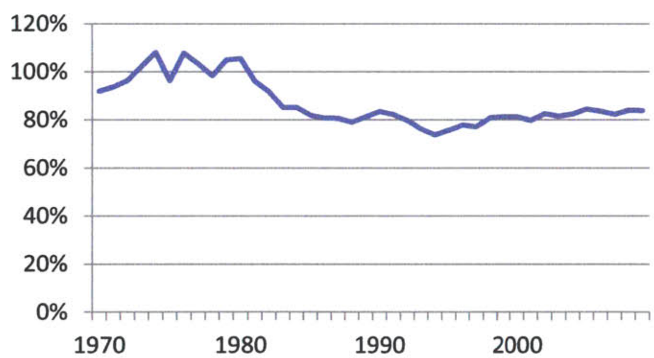
Source: Data for nuclear energy in the total primary energy supply (IEA data, 2012); avoided CO_2 emissions assumes nuclear power replaces coal on a direct content basis, applying a co-efficient of 95 t CO_2 per TJ for substituted oil (EEA, 2008 and Herold, 2003).

Notably, this analysis, like that used for the other cases, does not account for life cycle costs. For nuclear power plants, high amounts of CO_2 are linked to plant construction (Sovacool and Valentine, 2012) and can also be associated with the fuel cycle, which are not included in the above calculation. Additionally, the above calculation does not account for consumption increases which may have occurred because nuclear power was viewed as an inexpensive energy source relative to other fuels (i.e. rebound effect).

Energy Self-sufficiency

In terms of energy self-sufficiency, France evolved from essentially total dependence on imported oil and coal to reduced dependence overall and increased electricity exports. Figure A2 shows the change in net energy imports (imports minus exports) as a share of final energy consumption declining somewhat. What was 92% in 1970, peaked at 108% in 1976, and has since declined to 84%. Note: the amount can be above 100%, to account for stockpiling, etc.

Figure A2: Net Energy Imports as a % of Final Energy Consumed



Source: IEA data, 2012.

Main National Laws and Regulations related to Nuclear Power
(Excerpted from IAEA French Country Report, 2010)

Organization and structure

Ministry of Ecology, Energy, Sustainable development and sea (MEEDDM)

- Direction Générale de l'Energie et du Climat (DGEC)
- DGPR/MSNR
- Decree n° 2008-680 of 9 July 2008
- Ordinance of 9 July 2008
- Atomic Energy commission – Commissariat à l'énergie atomique (CEA)
- Code of Research, Legislative Part, Book III, Title III, Chapter II : Commissariat à l'énergie atomique -Articles L. 332-1 to L. 332-7 (Atomic Energy Commission).
- Ordinance n° 45-2563 of 18 October 1945 creating an atomic energy commission.
- Decree n° 70-878 of 29 September 1970 related to the Commissariat à l'énergie atomique (Atomic Energy Commission).
- Decree n° 72-1158 of 14 December 1972, as amended, implementing decree 70-878 related to the Commissariat à l'énergie atomique.
- Law of 9 March 2010 (2010-237): new name for the CEA, as Commissariat à l'énergie atomique et aux energies alternatives

Nuclear safety authority

- Law n° 2006-686 of 13 June 2006 on nuclear transparency and safety.
- Decree n° 2002-255 of 22 February 2002 creating the Directorate General for Nuclear Safety and Radiation Protection (DGSNR).
- Decree n° 73-278 of 13 March 1973, as amended, providing for the creation of the High Council for Nuclear Safety and the Directorate General for Nuclear Safety and radiation protection.

Institute for Radiation Protection and Nuclear Safety (IRSN)

- Law n° 2001-398 of 9 May 2001 establishing the French environmental safety agency (article 5 creating the Institute for radiation protection and nuclear safety).
- Decree n° 2002-254 of 22 February 2002 related to the Institute for Radiation Protection and Nuclear Safety.

National Agency for radioactive waste management (ANDRA)

- Environmental Code, Legislative Part, Book V, Title IV, Chapter II, art. L. 542-12.
- Decree n° 92-1391 of 30 December 1992 creating a national Agency for radioactive waste management.

Organization in the field of defence

- Decree n° 2001-592 of 5 July 2001 concerning safety and radiation protection in installations and nuclear activities used for defence purposes.
- Decree n° 78-78 of 25 January 1978 determining the competence or the General Secretary for National Defence (SGDN).
- Decree n° 2000-809 of 25 August 2000 determining the competence and the organization of the General Delegation for Armament (DGA).
- Decree n° 2001-417 of 11 May 2001 concerning the special commission for Basic nuclear installations classified as secret.
- Decree n° 2003-865 of 8 September 2003 providing for the creation of the interdepartmental committee for nuclear or radiological crises.

Regulatory provisions for nuclear installations

Basic nuclear installations (installations nucléaires de base – INB)

- Law n° 2006-686 of 13 June 2006 on nuclear transparency and safety.
- Decree n° 63-1228 of 11 December 1963 relating to nuclear installations.
- Ministerial Order of 27 April 1982 setting the characteristics of particle accelerators in so far as basic nuclear installations.
- Ministerial Order and Circular of 10 August 1984 concerning Basic Nuclear Installations design, construction and operation.
- Decree n° 85-449 of 23 April 1985 implementing to Basic Nuclear Installations Law n° 83-630 of 12 July 1983 concerning democratization of public inquiries and environmental protection.
- Ministerial Order of 11 March 1996 setting the limits above which factories for the manufacture or processing of radioactive substances and installations for the storage, the disposal or the use of radioactive substances, including waste, are considered as basic nuclear installations.
- Ministerial Order and Circular of November 1999 relating to the monitoring of the operation of the main primary circuit and of the main secondary circuits of pressurized water nuclear reactors.
- Ministerial Order of 31 December 1999 setting the general technical regulations for the prevention and limitation of detrimental effects and external hazards resulting from the operation of Basic Nuclear Installations.

- Ministerial Order of 12 December 2005 relating to pressurized nuclear equipments.

Liquid and gaseous effluent release and water intake

- Decree n° 95-540 of 4 May 1995 relating to liquid and gaseous effluent release and water intake in basic nuclear installations.
- Ministerial Circular of 6 November 1995 relating to Decree n° 95-540 of 4 May 1995 relating to liquid and gaseous effluent release and water intake in basic nuclear installations.
- Ministerial Order of 2 February 1998 concerning water intake and consumption and emissions of installations classified on environmental protection grounds subject to authorisation.
- Instruction of 20 May 1998 concerning licensing in the framework of decree n° 95-540 of 4 May 1995 relating to liquid and gaseous effluent release and water intake in basic nuclear installations.
- Ministerial Order of 26 November 1999 setting the general technical regulations concerning limits and conditions of effluent release and water intake in basic nuclear installations.
- Ministerial Circular of 17 January 2002 – Commentaries on the application of Ministerial Order of 26 November 1999 setting the general technical regulations concerning limits and conditions of effluent release and water intake in basic nuclear installations.

Installations classified on environmental grounds (installations classées pour la protection de l'environnement – ICPE)

- Environmental Code, Part. L., Book V, Title I, Chapter I, art. L. 511-1 to L. 517-2, concerning installations classified on environmental protection grounds.
- Decree n° 53-578 of 1st 20 May 1953 related to the nomenclature of installations classified on environmental protection grounds.
- Decree n° 77-1133 of 21 September 1977 implementing Law n° 76-663 of 19 July 1976 concerning installations classified on environmental protection grounds.

Nuclear installations classified as secret

- Defence code, Book III, Title II, Chapter II, art. L. 1333-1 to L. 1332-7.
- Decree n° 80-813 of 15 October 1980 amended related to installations classified on environmental protection grounds under the authority of the Defence Minister or subject to national defence secrecy protection rules.
- Decree n° 2001-592 of 5 July 2001 concerning safety and radiation protection in installations and nuclear activities used for defence purposes.

- Ministerial Order of 27 November 2003 relating to the organisation of the Ministry of defence for the operation of military nuclear systems and basic nuclear installations classified as secret, in the field of nuclear security.
- Ministerial Order of 31 January 2006 setting the general technical regulations for the prevention and the limitation of detrimental effects and external hazards resulting from the operation of basic nuclear installations classified as secret.

Electricity public utility

- Law 2000-108 of 10 February 2000 concerning modernization and development of the public electricity service, modified by Law 2003-8 of 3 January 2003 concerning gas and electricity markets and electricity public utility, and Law 2004-803 of 9 August 2004 concerning electricity and gas public utilities and electric and gas firms.

Radiation Protection

Protection of public and environment

- Public Health Code, Legislative Part, Book III, Title III, Chapter III : Ionizing radiation, art. L. 1333-1 to L. 1333-20 and Chapter VI : Penalties, art. L. 1336-5 to L. 1336-9.
- Public Health Code, Regulatory Part, Book III, Title III, Chapter III : Ionizing radiation, art. R. 1333-1 to R. 1333-93.
- Ministerial Order of 27 June 2005 related to the national network for collection of environment radioactivity measurements.

Protection of workers

- Labor Code, Legislative Part, Book I, Title II, Chapter II, art. L. 122-3-17 and L. 124-22 and Title III, Chapter I, art. L. 231-7-1
- Labor Code, Regulatory Part, Book II, Title III, Chapter I, art. R. 231-73 to R. 231-116 and Chapter IV, art. R. 234-20, R. 234-22 and R. 234-23
- Decree n° 75-306 of 28 April 1975 relating to protection of workers in basic nuclear installations.
- Decree n° 86-1103 of 2 October 1986 relating to protection of workers against ionizing radiations hazards.

Radiological emergency

- Ministerial Order of 20 December 2002 establishing the national reference guide on radiological hazards.

- Ministerial Order of 13 October 2003 relating to intervention levels in radiological emergency situations.
- Inter-ministerial Instruction of 7 April 2005 on the actions of the administration in case of an event leading to a radiological emergency situation.
- Ministerial Order of 4 November 2005 relating to information of populations in case of radiological emergency situations.

Regulatory regime for radioactive materials

- Code of Defence, Book II, Title III, Chapter III : nuclear materials and installations, art. L.1333-1 to L. 1333-14.
- Inter-ministerial Instruction of 28 March 1977 instituting the assistance regime for uranium prospecting.
- Law n° 80-572 of 25 July 1980 concerning protection and control of nuclear materials, as modified by law n° 89-434 of 30 June 1989.
- Decree n° 81-512 of 12 May 1981 concerning protection and control of nuclear materials.
- Decree n° 81-558 of 15 May 1981 concerning protection and control of nuclear materials in the field of Defence.
- Ministerial Order of 14 March 1984 concerning monitoring, confining, supervision and physical protection measures applicable to nuclear materials subject to declaration.
- Ministerial Order of 11 March 1996, repealing Ministerial Order of 24 November 1977 setting the characteristics of radioactive materials under special forms.
- Ministerial Order of 24 September 1996 setting the conditions for the assignment of nuclear materials to military use.
- Ministerial Order of 26 January 2004 concerning protection of national defence secrecy in the field of protection and control of nuclear materials, implementing decree n° 98-608 of 17 July 1998 concerning protection of national Defence secrecy.
- Circular of 26 January 2004 implementing Ministerial Order of 26 January 2004 concerning protection of national defence secret in the field of protection and control of nuclear materials.
- Ministerial Order of 16 March 2004 setting the technical conditions for the monitoring and the accountancy of nuclear materials.

Radioactive waste management

- Environmental Code, Book V, Title IV, Chapter II : Radioactive waste, art. L. 542-1 to L. 542-14.
- Law n° 2006-739 of 28 June 2006 relating to radioactive materials and waste

- Decree n° 94-853 of 22 September 1994 on the import, export and transit of radioactive waste between Community member states, as amended by decree 2002-460.
- Decree of 3 August 1999 approving the implementation and operation of an underground laboratory.
- Decree n° 99-686 of 3 August 1999 implementing article 14 of the Law of 30 December 1991 concerning research activities on the management of radioactive waste.
- Decree n° 99-687 of 3 August 1999 implementing article 6 of the Law of 30 December 1991 concerning research activities on the management of radioactive waste.
- Law n° 2000-174 of 4 March 2000 authorizing the approval of the Joint Convention on the safety of spent fuel management and on the safety of radioactive waste management.
- Law 91-1381 of 30 December 1991 concerning research activities on the management of radioactive waste

Civil Liability

- Law n° 68-943 of 30 October 1968 concerning nuclear civil liability.
- Decree n° 69-154 of 6 February 1969 related to the publication of the Convention on Third Party Liability in the Field of Nuclear Energy of 29 July 1960, as amended by the Additional Protocol of 28 January 1964 and by the Protocol of 16 November 1982 (Paris Convention).
- Decree n° 94-308 of 14 April 1994 related to the publication of the Convention of 31st January 1963 Supplementary to the Paris Convention of 29th July 1960, as amended by the additional Protocol of 28th January 1964 and by the Protocol of 16th November 1982 (Brussels Convention).
- Insurance Code, Legislative Part., Book IV, Title III- Chapter I : Extraordinary and nuclear risks, art. L. 431-4 to L. 431-7.
- Insurance Code, Regulatory Part., Book IV, Title III, Chapter I : Exceptional and nuclear risks, art. R. 431-27 to R. 431-29.
- Insurance Code, Regulatory Part, Book III, Title III, Chapter I : Technical provisions of others insurance operations, art. R.331-6.
- Decisions of 27 October 1977 concerning exclusion of small quantities of nuclear substances out of nuclear civil liability Convention, from the AEN Committee of Directors.
- Decree n° 91-355 of 12 April 1991 implementing article 4 of the Law 68-943 of 30 October 1968 defining the characteristics of reduced risks installations.

Nuclear Test-Ban

- Law 98-217 of 27 March 1998 authorizing the ratification of the Comprehensive Nuclear Test-Ban Treaty (CTBT).

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Chapter 7

Icelandic Geothermal Energy: Shifting Ground

We see Iceland as the world's lab for a decarbonized future.

– Ingibjorg Solrun Gisladottir, former Icelandic foreign minister and mayor of Reykjavik[1]

A. INTRODUCTION

The small island nation of Iceland lies at the center of powerful forces. Geographically, it bridges the North American and Eurasian tectonic plates, where seismic events (including volcanic eruptions) are common. Iceland is also a microcosm for some of the largest issues facing society today. It has vast stores of low carbon energy that are used to fuel its rising economy. While nearly all Iceland's electricity is derived from hydropower and geothermal energy (National Energy Authority/NEA, 2011a), 80% of the overall total is consumed by export-oriented manufacturing, principally aluminum smelters (Ministry of Environment, 2010). Within this path, local and international tradeoffs of energy choices are brought into sharp relief.

In this chapter, Iceland's harnessing of geothermal energy is considered. As a prime mover in the utilization of geothermal energy, about a quarter of the Iceland's electricity is powered by this form of energy, and roughly nine out of ten homes in Iceland are heated by it (Bjornsson, S., 2010; IEA, 2012). Iceland is also known internationally as a source of training and consulting on geothermal energy with a diverse industrial cluster

[1] Montavalli, 2008.

that has developed around it (Interviews, 2012; United Nations University Geothermal Training Programme/UN-GTP, 2012; Gekon, 2012).

The following highlights how fuel substitution, localized learning, and innovative spillovers reframed the Icelandic energy path. It begins with a discussion of the basics of geothermal energy. Next, the Icelandic geothermal transition is outlined, followed by an examination of key innovations in and determinants of geothermal energy adoption. It concludes with discussion of some themes that will be revisited in the comparative analysis.

B. BASICS of GEOTHERMAL ENERGY and RELATED TECHNOLOGY

Geothermal energy comes from the Earth's inner heat. It is produced by the decay of naturally occurring radioactive isotopes of uranium, potassium and thorium or from the primordial heat associated with the Earth's early development (World Energy Council/WEC, 2010; Canada Geothermal Energy Association/CANGEA, Undated). This thermal energy is contained in rock as well as in the steam or fluid found in fractures and pores within the earth's crust (Tester et al, 2005; Goldstein et al, 2012; IEA, 2011).

Different kinds of geothermal resources hold varying potentials (Table B1). Geothermal energy found in hot dry rock is estimated to contain the most potential for this particular renewable energy source at a quantity which is more than 200,000 times the current, global consumption of energy (IEA, 2012).

Table B1: Base Estimates of Worldwide Geothermal Resources by Type
(Total Thermal Content in situ)

Resource Type	**Total Thermal Energy** (EJ)
Hydrothermal (vapor and liquid dominated)	137,157
Geopressured*	569,730
Magma**	5,275,279
Hot Dry Rock***	110,780,865
Moderate to high grade	27,958,980
Low grade	82,821,884

*Source: Adapted from Tester et al, 2005, citing Mock et al (1997), Armstead (1983), Armstead and Tester (1987), Duchane (1994), Rowley (1982).Converted to EJ, based on 1 quad = 1.055 EJ. Notes: *To depths of 10 km and initial rock temperatures of >85C. **To depths of 10 km and initial rock temperatures of >650C. *** Includes hydraulic and methane energy content. Note: Assumptions vary relative to Figure E1 and Table E1, Chapter 1.*

A recent study of the global potential for geothermal-powered electricity, indicated that 45 EJ per year exists (12,500 TWh_e), equal to roughly 65% of all electricity generated in 2008 (IEA, 2011, citing Krewitt et al, 2009).[2] It also estimated the technical potential for direct use of geothermal energy at 1,040 EJ/year or 289,000 TWh_t, excluding the additional potential found in hot rock/offshore hydrothermal energy, magma and geo-pressured resources that may at some point be harnessed with more advanced geothermal technologies (Ibid).[3]

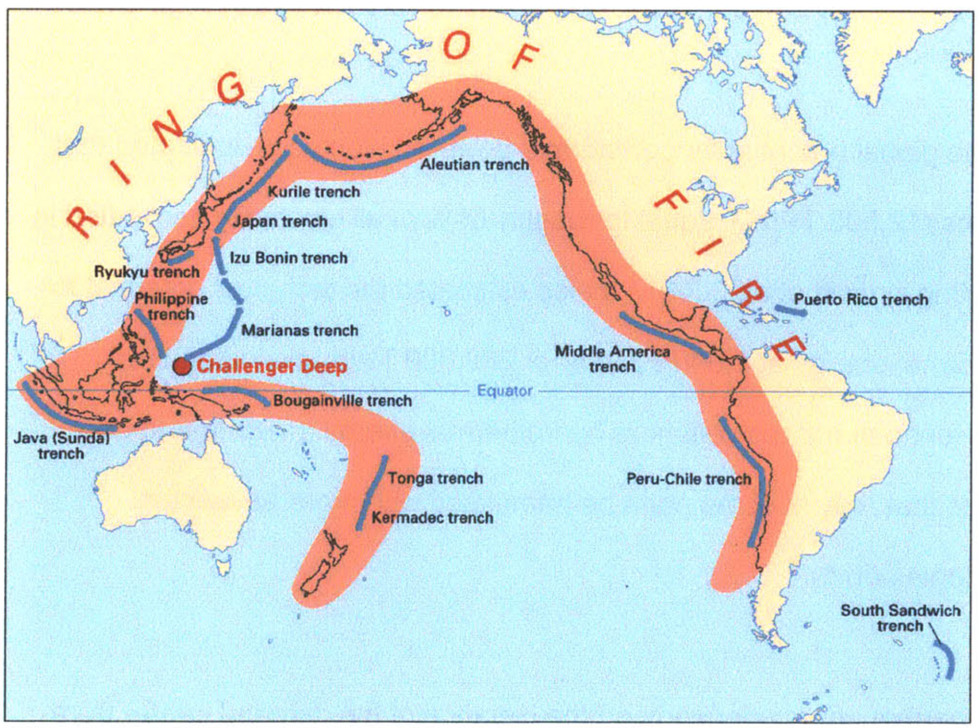
Harnessing of geothermal energy depends on the distance of the demand center from the resource, geological conditions, and costs, among other factors (IEA, 2011;

[2] TWh_e and TWh_t reflect terawatt hours of electric and thermal energy, respectively. Note: With different studies and views of potential, assumptions may vary.

[3] Advanced technologies include enhanced geothermal systems (IEA, 2011).

Thorsteinsson and Tester, 2012). It can be found practically anywhere (Union of Concerned Scientists/UCS, 2009). However, the highest quality resource is linked to geographic areas with a significant amount of tectonic plate interaction and active or young volcanoes (Ibid; US Geological Survey/USGS, Undated). One particular region known for this resource is the 'Ring of Fire' or Circum-Pacific belt, a zone encircling the Pacific Ocean (USGS, Undated; Figure B1). This area has tectonic and volcanic activity, enabling substantial amounts of heat to rise to the surface (Ibid).

Figure B1: Ring of Fire

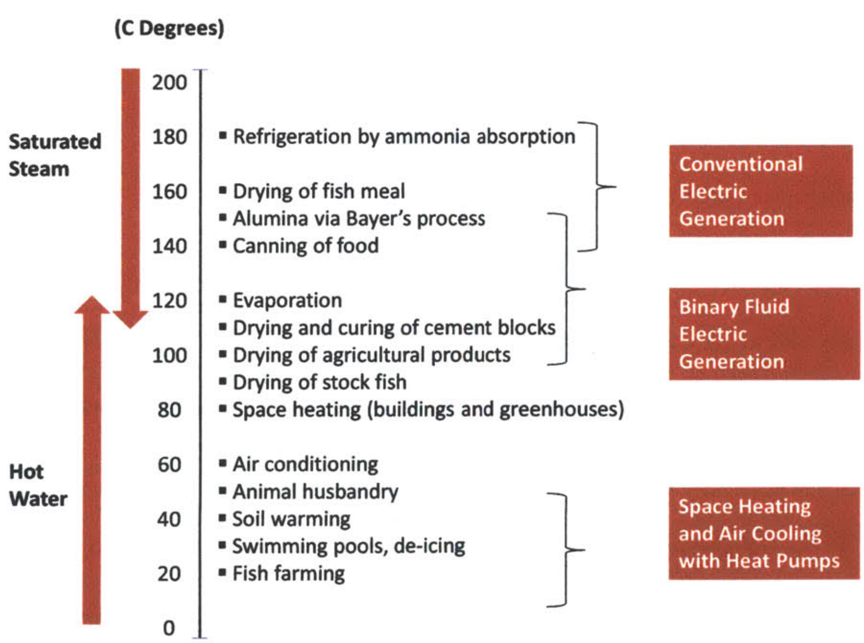


Source: United States Geological Survey, Undated.

To tap geothermal energy at scale, two primary means are employed: (1) direct use of steam or heated water, and (2) indirect use which converts energy into electricity

(Tester, et al, 2005; Kiruja, 2011). Applications depend substantially on the temperature of the resource. For use as electricity, geothermal resources are generally 100-150+°C (WEC, 2010; IEA, 2011). By comparison, geothermal energy use in heating can draw upon broader ranges of temperature and be used for a number of purposes including: space heating, heated pools, greenhouse and soil-heated treatments, aquaculture, and the melting of snow (IEA, 2011; Figure B2). In Iceland, low temperature geothermal energy (<150° Celsius/C) is utilized directly for heating. High temperature geothermal energy (200-400° C) is used primarily for generating electricity, and secondarily for heat in space heating, fish farming, industry, etc (Interview, 2012). Another way to utilize geothermal energy, done with ground source heat pumps, is not typically used in Iceland (Interview, 2012).

Figure B2: Lindal Diagram (Modified)



Source: Adapted from Kiruja, 2011.

Power Generation

When used for producing electricity, geothermal energy is suitable for centralized as well as decentralized (distributed) systems (Ibid). Unlike intermittent renewables, geothermal energy can be used as a base-load form of electricity. This means generation can meet the minimum amount of power provided by a utility or distribution company. The use of geothermal energy as a base-load is possible, since it generally does not have seasonal or weather-related flux and can be dispatched on demand (IEA, 2011).[4] Geothermal energy could also be used to meet peak demand, but effective processes and methods for load-following have yet to be developed (Ibid). An important distinction between geothermal energy and intermittent renewable energy in the power sector is that high penetration of geothermal energy does not impose load-balancing requirements on the system, as is the case with wind power (Ibid; see also Chapter 5).

There are two primary types of geothermal power plants: steam cycle and binary cycle. Each extracts hot water and steam from a borehole, then recycles warm water to extend the life cycle of the heat source (Union of Concerned Scientists/UCS, 2009).

Steam cycle plants, namely dry and flash steam designs, allow hydrothermal fluid (essentially high temperature water) to boil at which point steam is separated from brine and expands in a turbine (Valdimarsson, 2011). The brine can then be disposed by re-injection into the ground or be vaporized (flashed) at a low temperature (Ibid). Dry steam plants are used in about a quarter of today's global geothermal capacity and

[4] Note: Air-cooled binary geothermal plants are an exception, since their output is influenced by changes in air temperature (IEA, 2011).

involve geothermal steam being piped directly from a well to a turbine/generator (Ibid; IEA, 2011). In a flash steam model, used for about two-thirds of geothermal-installed capacity today, the hydrothermal fluid enters the well at high pressure and boils on its way up as the pressure is reduced (IEA, 2011; Interview, 2012). The mixture of water and steam enters a flash tank where steam and water are separated (Ibid). The steam then powers a turbine/generator equipment (Ibid). The water is eliminated or it is re-injected into the ground together with condensed water from the turbine.

In contrast to the steam cycle power plant, the binary cycle design draws on geothermal water or steam in a way which does not directly interact with the turbine/generation equipment, but rather warms a secondary fluid in a closed power generation cycle with a heat exchanger (Valdimarsson, 2011; UCS, 2009). The heat exchanger conveys heat from the geothermal fluid to the secondary fluid at which point cooled brine is eliminated or re-injected into the ground (Valdimarsson, 2011). This type of design is the fastest-growing in geothermal power plants, drawing upon low to medium temperature resources which are more widely available (IEA, 2011).

Generally, the choice of plant type is a function of the site and resource attributes along with cost considerations. If steam is directly emitted from the well, a dry steam model can be used. If high temperature water is released, the flash models may be utilized. If neither of the above two approaches is suitable, a binary cycle model may be employed with a heat exchanger (UCS, 2009).

In addition to the above technology, there is also an emerging process known as enhanced geothermal systems (EGS), which captures areas of heat in hot dry rock (HDR). Hot dry rock reservoirs are generally located at depths below those of traditionally used geothermal sources and can be utilized by sending high pressure water to break up rocks (Ibid). Once the rock is fractured, additional water is injected, which then heats and can be used as steam (Ibid). A key challenge for the commercial viability of EGS lies in the ability to efficiently and reliably stimulate multiple reservoirs (IEA, 2011).

Direct Use

Beyond the use of geothermal energy in the production of electricity, the resource can be harnessed directly for heating. Hot springs, for example, may be used in aquaculture or to warm greenhouses. Direct utilization of geothermal energy includes applications like district heating systems, as is the case in Iceland (NEA, 2010).

Ground-source Heat Pumps

Ground-source heat pumps offer another way to tap geothermal energy by moderating building temperatures. These devices leverage the year-round temperature of 50° F (10° C) that is generally found several feet below ground. Employing subsurface pipes filled with a conveyent, like air or antifreeze, a pump re-circulates the conveyent to push heat out in the summer and produces the reverse effect in winter (UCS, 2009). Particularly in regions with temperature extremes, these pumps are the most efficient heating/cooling system (Ibid).

Environmental Considerations

As with other energy sources, environmental considerations also exist with geothermal energy. Among these are sustainability, emissions and effluents, as well as prospective seismicity.

While geothermal energy is a renewable form of energy, its rate of use can outpace the rate of its replenishment. The key is to balance surface level releases of heat with fluid and heat recharging of the source reservoir (Krater and Rose, 2009, citing Rybach and Mongillo, 2006). Stepwise development is an approach to ensuring sustainability in a geothermal field, while minimizing long-term production costs (NEA website, Undated). Fundamentally, this entails streamlining the development of new and existing geothermal wells, based on the monitoring and measured use of initial, geothermal wells in a project area (Ibid).

Geothermal gases and fluids contain a range of elements and compounds. Geothermal gases, for example, can be high in sulfur, which, when emitted in an open system, can smell like rotten eggs and be toxic at certain levels. Greenhouse gases, like CO_2, can also be emitted from open geothermal systems, arising from the natural flux in geothermal processes. This release of CO_2 differs from that emitted during combustion of traditional fossil fuels (IEA, 2011). Table B2 shows the relative releases of these emissions by various forms of energy use. Today's newer geothermal plants are typically designed to be closed-loop with no direct operational release of carbon dioxide (Ibid).

Table B2: CO_2 Emissions by Energy Use

Energy Use	CO_2 Emissions
Low temperature applications of geothermal	• 1 g/kWh_e
High temp, hydrothermal fields, partially open-cycle, geothermal power or heat plants	• 0 to 740 g/kWh_e (Worldwide average: 120 g/kWh_e)
Closed –loop geothermal power plant systems*	• 0 g/kWh_e
Lignite/brown coal plant	• 940 g/kWh_e
Natural gas plant	• 370 g/kWh_e

*Source: IEA, 2011, citing Bertani and Thain, 2002, Bloomfield et al., 2003, and IEA, 2010. *Note: These assume geothermal fluids are re-injected below ground with no atmospheric loss of vapor or gas.*

Geothermal fluids can also contain heavy metals as well as radon, arsenic, boron, mercury and ammonia which can damage fresh water, if not managed properly (Krater and Rose, 2009). A related concern is tied to the presence of salt in geothermal fluid which can build up in system pipes. Here, corrosion and scaling must be monitored.

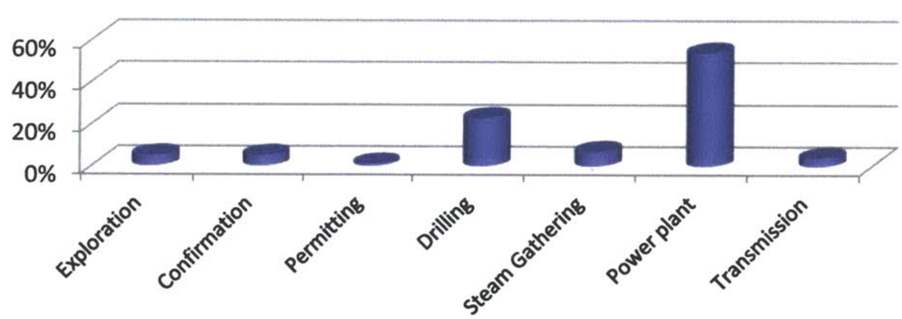
Another area of environmental concern with geothermal energy is seismicity. As with hydraulic fracturing in the oil and gas industries, the EGS process can induce seismic activity (UCS, 2009). Induced seismicity and micro-seismicity at EGS sites are currently being studied and will likely continue to be considerations that affect investment going forward (IEA, 2011).

Costs, Risk, Financing and Economics

In terms of the cost competitiveness of geothermal energy use, conditions will vary. In regions with high temperature hydrothermal resources, geothermal-based electricity is frequently competitive with new power plants that use conventional fuels (IEA, 2011). Use of binary plants may be done competitively, however costs will differ based on the plant size, the temperature of the resource and other geological conditions (Ibid). Geothermal heating can be competitive with district heating systems (Ibid).

Broadly speaking, geothermal energy projects have high, front-loaded capital costs for exploration, drilling and plant construction. A study by the Geothermal Energy Association (2005) outlined the breakdown of costs for geothermal plant development (Figure B3).

Figure B3: Typical Cost Breakdown for Geothermal Power Plants



Source: Geothermal Energy Association data, 2005.

Other than the construction of the plant itself, which comprises more than 50% of the costs, the study found drilling to be the most expensive component at roughly 25% of the total (GEA, 2005). Another estimate indicates that drilling could reflect a higher relative cost in the range of 40% of the total (Interview, 2012). An MIT Drilling Cost Index indicates that drilling costs have risen sharply since 2000, driven in large part by rising oil prices (Thorsteinsson and Tester 2010, referencing Augustine et al, 2006). Drilling inherently carries a high level of uncertainty and risk.

Uncertainty and large-scale front-end investment needs mean that debt financing and government support can play an important role in determining whether a geothermal project occurs. In so-called 'open markets', limited options exist for financing (IEA, 2011). Here, resource verification loans are an instrument which can assist in covering the cost of drilling and testing of production wells (Ibid). This tool, as the name suggests, funds the assessment of a resource, like geothermal energy. Co-financing, grants, partnerships, in addition to multilateral/bilateral bank funding are notable other means for addressing the financing challenge (IEA, 2011).

Multidimensional and Global Aspects to Geothermal Energy

Among fuel types, geothermal energy is a prime candidate for combined heat and power plants (CHP).[5] Essentially, heat emitted in electricity production is routed for secondary use in heating. This sustainable optimization of energy embodies the

[5] Combined heat and power plants can be traced to Thomas Edison's first commercial power plant. These plants are attractive for companies engaged in electricity and heat services, as well as water services. Because of the conduciveness of geothermal energy for CHP plants, there may be an overlap in industries and utility functions by geothermal energy-producing companies.

application of the 2nd law of thermodynamics which sets a limit on the overall thermal efficiency attainable by heat engines.

In 2010, globally installed geothermal power plant capacity was 10.9 GW with the average capacity per operating unit equaling roughly 20 MW (Bertani, 2010). Global data on geothermal energy in heating is less readily available.

C. ENERGY TRANSITION

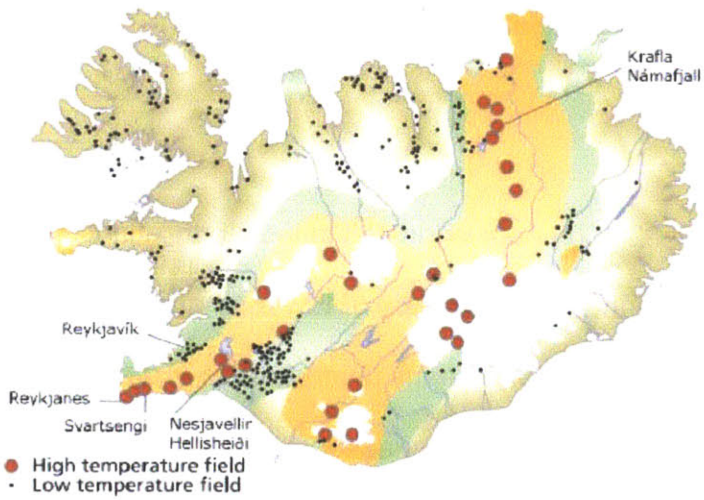
Iceland is an island nation of roughly 320,000 people located in the North Atlantic just south of the Arctic Circle (Statistics Iceland, 2012; Ministry of Environment, 2010). After a volcanic eruption in 1783, the area was declared nearly uninhabitable (Tomasson, 1980), and yet it has risen from being one of the poorest nations in Europe at the beginning of the 20th century to become a top-ranked country in the United Nation Development Program's human development index (see Drivers section). It is also a leader in renewable energy use, namely geothermal energy and hydropower (Ministry of the Environment, 2010; Islandsbanki, 2010).

Situated in an active tectonic zone, a quarter of Iceland is a volcanic area (Einarsson, 1991).[6] Iceland has over 200 volcanoes and 600 hot springs, providing substantial

[6] The tectonic plates are separating at a rate of 2 centimeters per year (Islandsbanki, 2010).

geothermal potential (NEA, 2010).[7] Figure C1 illustrates the distribution of high and low temperature geothermal resources.

Figure C1: High and Low Temperature Geothermal Areas in Iceland



Source: Jonasson and Thordarson, 2007.

With more than one tenth of its land mass covered by glaciers, Iceland is also home to waterfalls and rivers which provide abundant hydropower potential (Ministry of the Environment, 2010; Islandsbanki, 2010). Currently, 65% of Iceland's primary energy supply is sourced from geothermal energy – possibly the largest share of any country's energy mix in the world (IEA, 2012; Bertani, 2010, citing Ragnarsson, 2010). Essentially 100% of its electricity is derived from RETs – an estimated 75% from hydropower and 25% from geothermal energy (Ibid). In terms of heating, roughly 90% of space heating

[7] Geysers, based on the Icelandic word to gush, are spouting hot springs that are quite prevalent in Iceland.

in Iceland comes from geothermal energy (Bjornsson, S., 2010). For basic totals, space heating utilizes the most geothermal energy among all applications at 25 PJ/year (Ibid). Installed capacity for electricity from geothermal power was 575 MW_e in 2010 (GEA, 2010).

Historical Background

Iceland has a long relationship with geothermal energy. Icelandic sagas – oral histories of the 10th and 11th centuries that were passed on in written form in the 13th and 14th centuries -- indicate that the early settlers built homes in 874 A.D. near hot pools, using geysers for bathing, washing and cooking in "the Bay of Steam," today's Reykjavik (Einarsson, 1991; Icelandic Sagas, Undated). In the 13th century, sulphur was extracted from Icelandic steam for use and export in products like gunpowder (Ibid). Production of salt from seawater with geothermal heat was another attempt to harness the energy of the earth in the 18th century. Experiments with geothermal energy in gardening were also tried in the late 19th century (NEA and Ministries of Industry and Commerce/MIC, 2006). Yet it wasn't until the 20th century that geothermal utilization began at significant scale (Einarsson, 1991).

The application of geothermal energy to heat houses in Iceland dates to 1908. At that time, farmer, carpenter, author, salesman and entrepreneur Stefan Jonsson piped steam from hot springs onto his farm (Thordarson, 2008). By the 1920s, schools, hospitals and institutions were being sited near geothermal areas (Einarsson, 1991). Rising demand for electricity and knowledge that geothermal energy was used in

Lardarello, Italy led some in Iceland to try exploring for the resource with an abandoned drill from gold exploration (Jonasson and Thordarson, 2007; UNDP et al, 2000). By the 1930s's Iceland introduced what may have been the world's first, large-scale municipal district heating service fueled with water from hot springs and boreholes through a 3 km pipeline (Ibid; (Loftsdottir and Thorarinsdottir, 2006; Einarsson, 1991; Jonasson and Thordarson, 2009). One of the earliest Icelandic houses to be heated with a tapped borehole is shown in Figure C2.

Figure C2: One of the First Houses in Iceland to be Heated by Geothermal Water by Way of a Geothermal Borehole at Sudurreykir

Source: Jonasson and Thordarson, 2009.

As the population of Reykjavik grew, more than doubling in the 1940s alone, geothermal use expanded (Jonasson and Thordarson, 2009; Loftsdottir and Thorarinsdottir, 2006). To adapt with shifting conditions, the government in 1946 instituted the Electricity Act, creating the State Electricity Authority with responsibility for advancing knowledge on geothermal and hydrologic resources (Loftsdottir and Thorarinsdottir, 2006).

By mid-century, oil burners had replaced coal furnaces, a Geothermal Department was established in the State Electricity Authority, and the government launched a rural electrification program (Thordarson, 2008; Ingimarsson, 1996). Power-intensive industry also began to emerge with cement and fertilizer producers (Hjarlmarsson, 2009; Dunn, 2000; Loftsdottir and Thorarinsdottir, 2006). In 1947, the State Drilling Company was formed and the Act on the Geothermal Energy Fund was established in 1961 (Interview, 2012). The Geothermal Fund, later combined with another energy fund, was used to provide low interest loans covering typically 60% of total drilling costs and to share risk undertaken by developers with the State (Ingimarsson, 1996).

The economy played a central role in Iceland's 20th century energy development. As Iceland battled with the British over fishing rights, and fluctuations in the fish market impacted the domestic economy, governmental attention turned to the prospect of developing power-intensive manufacturing by utilizing natural resources (Landsvirkjun, Undated A; Loftsdottir and Thorarinsdottir, 2006; Del Giudice, 2008; Hjalmarsson, 2007; Interview, 2012). Until mid-century, power was produced by many small hydropower plants owned by localities (Interview, 2012). In the 1960s, a task force identified new markets powered by scaled energy, and Swiss aluminum producer Alusuisse agreed to site an aluminum smelter in Iceland (Landsvirkjun, 2009; Logadottir and Lee, unpublished).

In 1965, Landsvirkjun was formed to build and operate power generation plants for power-intensive industries and the general public (Landsvirkjun, Undated A). Prior to this, electrification had been handled by the national government and municipalities, but financing of major energy projects was a challenge (Landsvirkjun, 2009). In conjunction with Landsvirkjun's establishment, a 45 year contract was signed with Alusuisse to sell electricity at low rates (Logadottir and Lee, unpublished; Interviews, 2011-2012). Landsvirkjun then began work on the Burfell hydropower dam, which would provide electricity for the aluminum plant.[8]

As the 1960s came to a close, Iceland's first foreign-owned aluminum smelter came on-line with power from a new 210 MW hydropower plant built to service the aluminum company's long-term, take-or-pay contract (guaranteed purchase) together with any growth in general demand (Valfells et al, 2004; Halfdanarson, 2008). The first industrial application of geothermal heat became operational with a diatomite plant (Einarsson, 1991; Hjarlmarsson, 2007).[9] A program was also established at the State Electricity Authority's successor, the National Energy Authority, to study high temperature geothermal fields (Interview, 2012) and the country's first commercial geothermal power plant was launched at Bjarnarflag in northeast Iceland in 1969 (Loftsdottir and Thorarinsdottir, 2006; Bertani, citing Ragnarsson, 2010; Islandsbanki, 2010). At this

[8] The World Bank provided about one-third of the investment capital and was heavily involved in the early shaping of Landsvirkjun's structure (Landsvirkjun, 2009 and Undated A; Davidsson, 1986). The company was structured so that the State and municipality each owned 50% (Ibid). The Bank also emphasized that Landsvirkjun should design its operations in order that projects be undertaken through international tenders with external engineering consultants engaged in project management and oversight of subcontractors (Landsvirkjun, 2009).

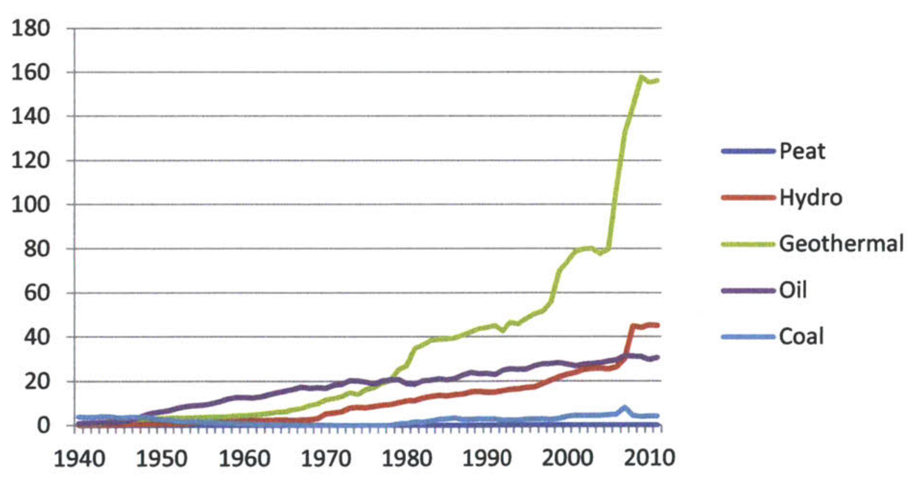
[9] This plant produced 28,000 tons of diatomite filters for exports on an annual basis from 1967 until its closure in 2004 (NEA, Undated). It was one of the world's largest industrial users of geothermal energy, utilizing the energy to dry diatomaceous earth sourced from Lake Myvatn (Ibid).

juncture, fishing/seafood exports accounted for 90% of export revenue (Islandsbanki, 2010) and, by some accounts, Iceland was still a developing country (Interviews, 2011-2012).

Iceland's Modern Geothermal Energy Transition: 1970-the present

By 1970, Iceland's geothermal energy transition was well underway. The country had a 60-year track record of geothermal use in heating (40 years on a commercial basis) and, more recently, a commercial launch of its geothermal-backed electricity (Thordarsson, 2008; Jonasson and Thordarsson, 2007). Iceland's shift from coal and oil, which had dominated its energy mix in the first half of the 20th century, was already evident (Figure C3).

Figure C3: Total Primary Energy in Iceland (PJ)



Source: Orkustofnun/National Energy Authority of Iceland (NEA) data, 2012.

In the following decades, the geothermal transition played out on three tracks, one in direct heating, primarily space heating; one in combined heat and power (CHP); and a third with electricity which principally powered heavy industry subsidiaries of foreign companies.

Before discussing the transition, it's useful to consider two divergent views of energy development which prevailed in Iceland in the 1970s.

Jakob Bjornsson, Director General of the National Energy Authority, wrote in an article on conservation and hydropower in Iceland:

> If the Icelandic nation has ambitions of living in a country with comparable material standards of living to the best found elsewhere in the world, it needs to make maximum use of the country's resources, which in return entails, as it were, a total reformation of the country itself. These two things are inseparable. .... there may be some that take the view that economic progress on a par with other countries is not necessarily a goal worth aiming for. Against such a view there is nothing to say. But is it something the majority of the nation will go along with (Magnason, 2008, citing Bjornsson, J., 1970)?

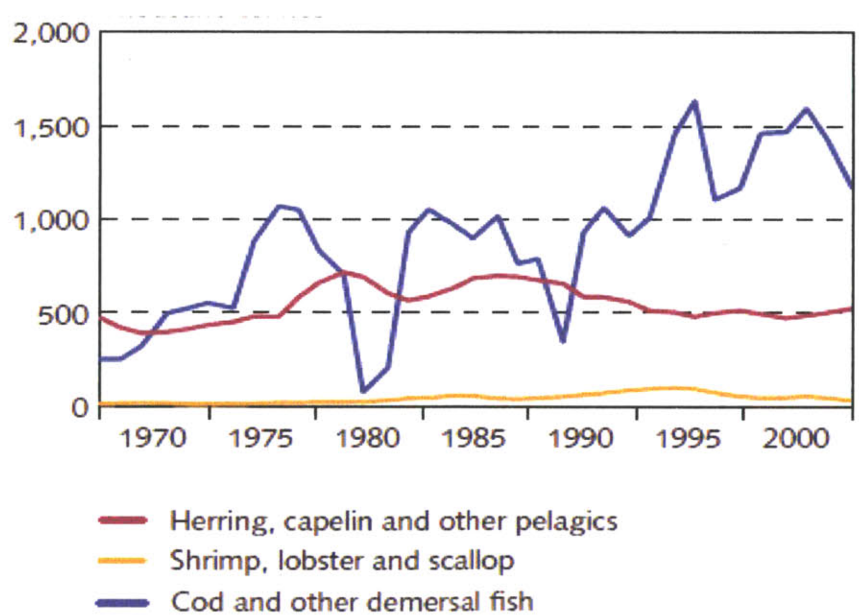
Halldor Laxness, a 1955 Nobel Prize winning novelist and Icelander, saw it differently:

> The problem is the unquestioning faith of the people at the National Energy Authority in filling this country with endless metal smelters. For it presents a grave danger to the land and its community when a group of men in suits, at the say-so of their slide rules, sets out to obliterate as many of the places we hold sacred as they can in as short a time as possible, drowning familiar settlements in water (twelve kilometers of the Laxa valley are set to be submerged, according to their plans), and given the chance, declaring war upon everything that lives and draws breath in Iceland (Magnason, 2008, citing Laxness, 1971).

Intersecting these views is the concept of resource-based development (Sachs and

Warner, 1997; Barbier, 2005), which in the context of Icelandic energy may be found in the utilization of abundant, low carbon energy to fuel mostly foreign-owned heavy industry. This strategy began in Iceland in the 1960s, based on long-term contracts, low rates, and special terms or rights associated with taxes, fees, and financial obligations (Logadottir and Lee, unpublished, citing various).[10] It propelled Iceland's economic development, particularly in later decades (discussed below and under Drivers). Yet, in the 1970s, this approach was considered by some as a way to protect the economy from extreme fluctuations caused by the fish industry dependent on cod (Figure C4) (Bjornsson, S., 1970; Sedlabanki Islands, 2005; Interviews, 2011-2012).

Figure C4: Fish Catch by Icelandic Vessels *(Thousand tonnes)*

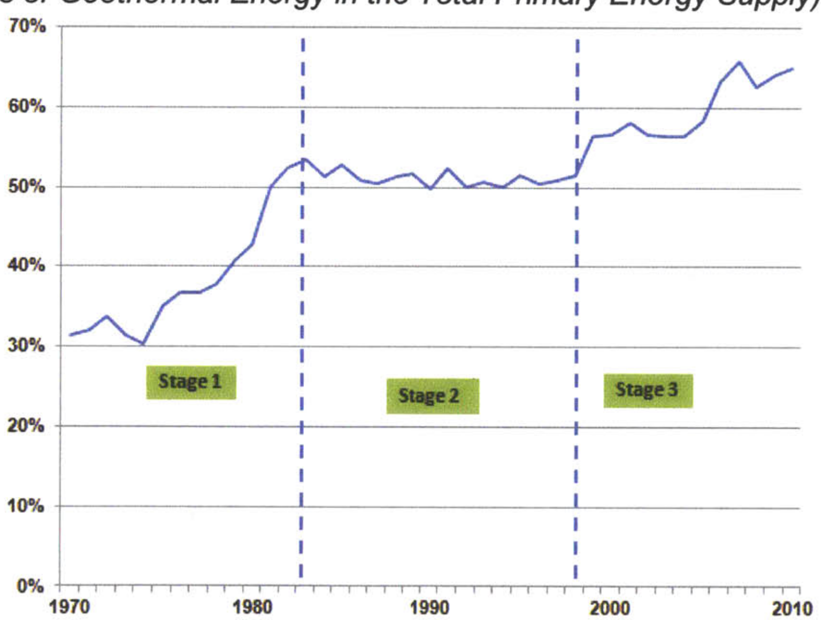


Source: Sedlabanki, 2005, referencing Statistics Iceland.

[10] For a detailed discussion of special terms, see Logadottir and Lee, Unpublished.

Notably, expeditious action was deemed to be important, by some, because nuclear energy was viewed as having the potential to become inexpensive within the next 20 years, thereby rendering Icelandic geothermal energy uncompetitive for future foreign investors (Bjornsson, S., 1970). This energy-industrial strategy would be tested in the years which followed. Three stages of Iceland's geothermal energy transition are considered next: 1970-1983, 1984-1997 and 1998 to the present (Figure C5), reflecting hybridized change.

Figure C5: Stages of Icelandic Geothermal Energy Development
(Shares of Geothermal Energy in the Total Primary Energy Supply)



Source: IEA data, 2012.

Stage 1: Displacement and Build-up (1970-1983)

Broadly, the first stage of Iceland's modern geothermal energy transition was characterized by concerted efforts of the national government, municipalities and energy companies to extend the geothermal heating infrastructure. Resource exploration continued from work of earlier eras. Adaptations in technology, processes and utilization occurred.

The period opened with the Swiss-owned Icelandic Aluminum Company LTD (ISAL) formally launching the Burfell hydropower plant, as Iceland joined the European Free Trade Association (EFTA) (Halfdanarson, 2008). A conflict in the Laxa- Myvatn community over a hydropower project raised questions about the country's energy path in relation to the role of conservation (Olafsson, 1981). These concerns resonated with earlier-mentioned positions articulated by Bjornsson and Laxness (Bjornsson, S., 1970; Magnason, 2008, referencing Bjornsson, J., 1970, and Laxness, 1971), and would reemerge in the decades to come.

Change could also be seen within the government. The Centre-Right Independence Party that had led during the previous decade was followed by a succession of shifts in office holders between 1971 and 1983 (see Appendix). In policy terms, the energy agenda changed from a focus on energy-intensive exports to priorities associated with interconnection of power networks and in meeting increased demand through smaller power plants (Interview, 2012; Palsdottir, 2005).

At the time of the first oil shock, 52% of Iceland's total primary energy supply consisted of oil imports (IEA, 2012). About 43% of Iceland used geothermal energy for heating

(Bjornsson, S., 2006) and roughly 1% of electricity was derived from geothermal energy (IEA, 2012). The oil shocks effectively spurred government, municipalities and energy companies to eliminate the use of oil in space heating (Interviews, 2011-2012). This was carried out by harnessing large amounts of the geothermal resource, which up to this point, had included the low temperature resource found in non-volcanic hydrothermal areas (< 130° C) (Ibid; Bjornsson, S., 1970; Arnorsson, 1975). Yet studies had begun of the higher temperature energy resource in the volcanic hydrothermal areas for use in electricity and industry (Bjornsson, S., 1970; Arnorsson, 1975).[11] In regions where geothermal water was not found, electricity was used to replace oil in heating (Ibid).

In 1975, National Energy Authority scientist Stefan Arnorsson described the contemporary expansion of geothermal use in Iceland as due, in part, to deep drilling at 1,500-2,000 meters and hydraulic cracking of the rock, which increased the permeability and yield from the holes (Arnorsson, 1975). Development was expected to support the rest of Reykjavik and surrounding communities in meet heating needs (Ibid). Additional initiatives to expand were similarly underway in outlying communities (Ibid).

One such region that had begun to develop geothermal energy was the Sudurnes in Southwest Iceland. The Grindavik town council and others were aware of Icelandic towns displacing oil with geothermal energy in district heating, so initiated drilling in

[11] See Appendix Timeline and Bjornsson, S. (1969). Aaetlun um Rannsokn Hahitasvaeda (A Program for Exploration of High Temperature Geothermal Fields). Skyrsla, Orkustofnun, Reykjavik.

1971 (HS Orka, 2010). When a high temperature geothermal reservoir (240° C) was struck with water containing large amounts of minerals and salinity, heat exchange methods were necessary to harness the resource (Ibid; Albertsson et al, 2010).The National Energy Authority designed a plant to leverage the geothermal resource (Ibid; Bjornsson, G. and Albertsson, 1985) and area municipalities elected individuals to oversee plant implementation (Ibid). Shortly thereafter, the Icelandic Parliament (Althingi) passed Act No. 100/1974 establishing Hitaveita Sudurnesja to serve the community with geothermal-based production and distribution of hot water/heating services (Ibid). Ownership of the company was shared between the national government (40%) and the seven municipalities involved (Ibid).

Another major project of the time was initiated to install a 60 MW_e geothermal power plant at Krafla in the Northern region of Iceland. As construction commenced in 1976, volcanic activity hindered progress (Interview, 2012; Landsvirkjun, 2009). Some questioned whether the area conditions were adequately understood, as others pointed to the eruption altering the physical characteristics of the region (Interviews, 2011-2012). In either case, the Krafla project was revised to install merely 30 MW_e (Loftsdottir and Thorarinsdottir, 2006) and interest in developing geothermal power plants was deferred for nearly two decades (Interviews, 2011-2012). Another 30 MW_e would not be installed at Krafla until 1997 (Ibid). The circumstances of the Krafla project provided early experience on the need for stepwise development of geothermal capacity, which would align with ideas about sustainable development that later emerged (Interview, 2012; World Commission on Environment and Development, 1987).

Despite the difficulties experienced with the Krafla plant, geothermal energy development continued in areas like exploration for resources and expansion of space heating infrastructure. In line with this, combined heat and power (CHP) plants were also incrementally developed to harness overall efficiencies at Svartsengi and later Nesjavellir plants (Interview, 2012; Loftsdottir and Thorarinsdottir, 2006; HS Orka, 2012; Reykjavik Energy, 2012). Sales of the CHP-based geothermal electricity were limited initially by Landsvirkjun's monopoly and stipulations in early, geothermal company charters (Interviews, 2011-2012).[12] However, rules shifted during the next three decades, allowing companies like Hitaveita Sudurnesja to expand more fully into the power generation line of business (HS Orka, 2012; Interviews, 2012).

Advances with Icelandic geothermal energy progressed in non-energy sectors. The Blue Lagoon, for example, was formed in 1976 with the geothermal waste fluid from the Svartsengi geothermal plant. Over the course of the next few decades, the Lagoon would become a spa and tourist attraction as well as a treatment center for psoriasis. In addition, beauty products were developed with minerals derived from the Lagoon (Gudmundsdottir et al, 2010; Blue Lagoon, Undated). Other than the Blue Lagoon, developments in fish farming, services which de-iced public access areas, and greenhouses would similarly leverage the natural heat of geothermal energy (Bjornsson, 2010; see Innovations).

[12] Parliament approved the creation of municipal energy companies to focus on heat and hot water services.

In 1978, 23% of the population used oil in heating, but paid 60% of the space heating costs – a sign that costs were skewed by oil prices (Thordarson, 2008). That same year, the NEA partnered with the United Nations University to establish the Geothermal Training Program in Iceland. The objective of the Training Program was to assist developing countries with substantial geothermal resources in order to enhance expertise through specialized post-graduate courses (Ibid). Over the next three decades, this center would educate nearly 500 scientists and engineers from 50 countries (UNU-GTU, 2012).

As the first stage of Iceland's modern energy transition came to a close, negotiations with Alusuisse became entangled in energy pricing and taxation issues (Interview, 2012; Palsdottir, 2005). Public concerns over the domestic presence of foreign-owned plants also led to political demands that Icelanders retain majority ownership (Interviews, 2012). This issue would repeat in later years (Stage 3). It can be explained in part by Icelanders' long history with foreign rule and the importance they attached to independence (Interview, 2012; Hjalmarsson, 2009).

The period ended with geothermal energy surpassing other fuels in Iceland's energy mix, rising from 31% to 53% of the total energy supply (Figure C3). For electricity, there was little movement with geothermal energy rising from 1% to 5% (IEA, 2012). Landsvirkjun became a full-fledged national power company in 1983, ultimately acquiring the Krafla geothermal plant, together with the related transmission network (Landsvirkjun, 2009; Palsdottir, 2005; Interview, 2012). In conjunction with

Landsvirkjun's expansion, its company ownership was modified to: State (50%), municipality of Reykjavik (45%) and now Akureyri (5%) (Ibid).

Stage 2: Stasis (1984-1997)

The next stage began with a new government. Landsvirkjun also emerged with a recently changed mandate from that of a regional player to the National Power Company. The government's focus returned more fully to promoting foreign investment based on indigenous energy, yet the period showed little change in energy and heavy industry patterns until the end. Environmentalism gained ground in the 1990s.

As the second stage of Iceland's modern geothermal energy transition opened in 1984, 83% of the Icelandic population used geothermal energy in space heating compared to 43% in 1970 (Loftsdottir and Thorarinsdottir, 2006). A revised agreement was negotiated with Alusuisse, the terms of which included an increase of 50% in energy pricing and benchmarking tied to aluminum prices (Interview, 2012).

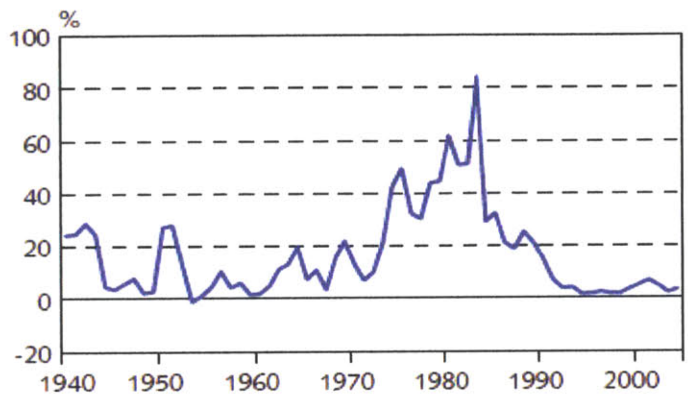
Governments for roughly the next two decades would alternate between the two centrist parties -- the Center-Right Independence Party and Center-Left Farmers Party (see Appendix). Once the heating infrastructure was in place,[13] policy related to energy would focus on efforts to attract foreign investment with energy (Interview, 2012).

Around this time, Iceland experienced record high inflation (Figure C4; Sedlabanki Islands, 2005). Recovery would follow in the latter 1980s, driven by tighter monetary and exchange polices, income policy focused on inflation reduction, and sweeping

[13] All major power stations were connected to the grid by 1984 (Loftsdottir and Thorarinsdottir, 2006).

structural reforms (Sedlabanki Islands, 2005). The reforms brought inflation generally in line with what Iceland's major trading partners were experiencing (Ibid).

Figure C4: Percentage Change between Annual Averages in Consumer Price Indexed Inflation



Source: Sedlabanki Islands, 2005, referencing Central Bank of Iceland.

In the international arena, the Chernobyl nuclear accident and a decline in oil prices marked a turning point for Icelandic energy. The collapse of global oil prices materialized domestically with oil becoming cheaper than geothermal energy. The debt of a number of district heating companies reliant on geothermal energy would be taken over by the national government (Interviews, 2011-2012).[14]

[14] A committee appointed in 1990 by the Ministry of Industry to report on the equalization of energy prices indicated that the Icelandic Treasury absorbed part of the debt of the geothermal district heating services in the period 1983 – 1990 for:

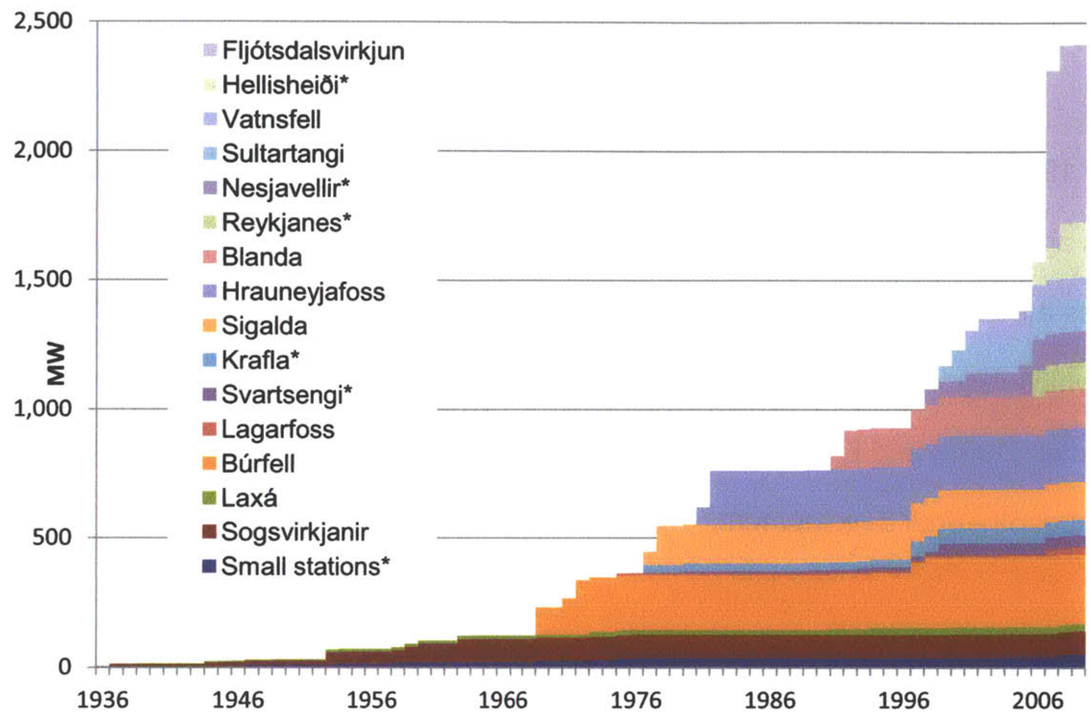
- Egilstadir and Fell: ISK 6 million (1983) and 2.5 million (1984)
- Svalbardseyri ISK 0.5 million (1983)
- Hrisey ISK 1 million (1983)
- Sudureyri ISK 4.5 million (1983) and 2 million (1984).

Following the nuclear accident in Chernobyl, discussions began with individuals in Great Britain about the possibility of exporting electricity from Iceland by way of a subsea cable (Palsdottir, 2005). Earlier proposals of this kind had been reviewed by the NEA in 1975 and 1980 for Scotland (Ibid). The NEA concluded that the cost would be equivalent to that of coal and nuclear in the import market, but the upcoming liberalization in the United Kingdom meant that there would be uncertainty for long-term contracts. New feasibility studies were completed, indicating that such a project was technically feasible (Ibid). More studies and discussions would follow (Ibid).

Domestically, a period of investment stagnation grew despite the Icelandic government's focus on attracting foreign investment. During this time, Landsvirkjun was criticized for implementing the Blanda hydropower project without any significant, new power demand (Landsvirkjun, 2009). Following this, no geothermal or hydropower projects were added during the remainder of the 1980s or early 1990s (Figure C5).

- Akranes and Borgarfjordur ISK 220 million (1987)
- Akureyri ISK 100 million (1987)
- Vestmannaeyjar ISK 89 million (1987)
- Hella and Hvolsvollur ISK 48 million (1987) and 20 million (1990) (Interview, 2012, referencing the committee report).

Figure C5: Installed Capacity of Geothermal* and Hydropower Plants in Iceland



*Source: Adapted from NEA data, 2011. Note: Geothermal power plants are marked with * and include Krafla, Svartsengi, Nesjavellir, Reykjanes, Hellsheidi. Geotherrmal plant Bjarnarflag is included with small stations.*

In an effort to rekindle foreign investment, the government of Iceland established a professional marketing office in 1988 to bridge the Ministry of Industry and Commerce with Landsvirkjun (Mackay and Probert, 1996; Palsdottir, 2005; Interviews, 2011-2012).[15] Promotional materials were circulated throughout Europe emphasizing the "Lowest Energy Prices" in Iceland together with the lowest wages and taxes (Palsdottir, 2005, Magnason, 2008). However, it wasn't until the mid 1990s that new contracts for aluminum or other heavy industry were secured. The market for global metals experienced a decline in demand due in part to the economic recession (Mackay and

[15] This formalized marketing work that had been underway (Interview, 2012).

Probert, 1996). Supply dumping by former Soviet states also had a dampening effect (Ibid; Interviews, 2011-2012).

In the early 1990s, Iceland joined the European Economic Area/EEA (Halfdanarson, 2008). This agreement offered a path toward increased trade within the European Union (EU), and as a consequence of this membership, Iceland needed to take account of EU directives which required a level playing field for trade. The Act on Environmental Impact Studies (1993) and Electricity Act (2003) were two legislative outgrowths that would affect geothermal development.

Environmental forces emerged more palpably in relation to energy in the 1990s. Up until then, high profile conservation efforts were on occasion, such as in Halldor Laxness' writing (Magnason, 2008, citing Laxness 1971); or in project specific opposition, like that tied to the Laxa-Myvatn conflict of 1970 (Olafsson, 1981; Halfdanarson, 2009; Interviews, 2011-2012). Yet international changes, including the release of the Brundtland Commission report and strengthening ideas about inter-generational equity resonated with some Icelanders' deep, national concern about their natural resources (Interviews, 2011). Public interest in the environmental impacts of hydropower projects and heavy industry also became much more visible, as international NGOs, like Greenpeace and the World Wildlife Fund, became more involved domestically (Halfdanarson, 2008; Interviews, 2011-2012). In 1997, the NGO Iceland Natural Conservation Association was formed (Grist, 2005). Other organizations, like Saving Iceland, subsequently focused on protecting Iceland's wilderness from heavy industry

(Saving Iceland, 2012). During this period the government established a Ministry of the Environment and published a white paper, highlighting the need for a long-term plan for energy use (Steingrimsson et al, 2007, citing Government of Iceland, 1997; Interview, 2011).

Long-awaited economic growth appeared in the mid-1990s with replenished fisheries, a global economic recovery, export increases, and new investments in the aluminum sector (Sedlabanki Islands, 2005; Landsvirkjun, 2009). For the Icelandic energy industry that had served a mostly saturated and insular market, new contracts with foreign companies in heavy industry were game-changers. Beginning in 1995, contracts were signed to enlarge the ISAL smelter in Straumsvík, to construct a new 60,000 ton aluminum plant for Columbia Ventures, and to enlarge a ferro-silicon plant installed in the late 1970s (Interview, 2012; Palsdottir, 2005).[16]

The period ended with geothermal energy in electricity and heating reflecting negligible changes. The share of geothermal energy rose from 5% to 7% in the electricity mix, but it was unchanged as a share of the total primary energy supply at 51% (IEA, 2012).

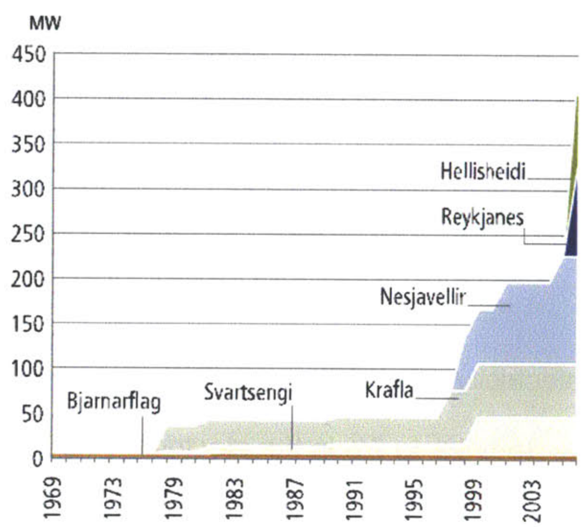
[16] By this time, the industry convention for aluminum plant production had also increased to at least 360,000 tons (Interview, 2012). In energy terms, this translated to the need for a power plant of roughly 600 MW (Ibid). Rather than constructing such a plant and 'growing into' that capacity, the National Power Company needed to implement a plan to develop several power plants with the capacity of 50-150 MW to meet new project needs (Ibid).

Stage 3: Acceleration, Planning and Rethinking (1998- the present)

In the third stage of Iceland's geothermal energy transition, a multitude of forces came into play. Environmental regulation and market liberalization altered the playing field. Geothermal energy emerged with an increasingly important role in the Icelandic energy-industrial strategy. A meltdown in the banking industry and domestic ownership concerns over privatization of a publically-owned energy company would also factor.

Beginning in 1998, a major growth spurt occurred in geothermal energy use in Iceland. New entrants and production expansion within heavy industry drove rapid scaling of geothermal power capacity alongside that of hydropower capacity (Figure C5 and C6).

Figure C6: Installed Capacity of Geothermal Power Plants



Source: NEA and Ministries of Industry and Commerce, 2006.

Environmentally, numerous new dynamics were in play. Efforts to formulate a Master Plan were launched in 1999 by the Ministry of Industry, Energy and Tourism and the Ministry of the Environment to review prospective geothermal energy and hydropower projects, based on criteria for energy efficiency, economics, environmental impacts, and social/cultural value (Steingrimsson et al, 2007; Interviews, 2011).[17] This process was implemented in two phases with participatory review by a mix of committees and experts (Ibid; Steingrimsson et al, 2007; Rammaaaetlun, Undated). Forty-three projects were reviewed in the first stage (19 hydropower and 24 geothermal) (Steingrimsson et al, 2007; Ketilsson et al, 2010). Based on a weighted scorecard ranking system, geothermal projects were largely found to be much more favorable (Ibid).

A second phase of the Master Plan began in 2004, evaluating all geothermal projects in high temperature fields plus new or revised hydropower projects (NEA, Undated). Findings from this were published in 2010. Among the 32,356 GWh/year of projects that were reviewed, the most acceptable were those classed in the 'harnessing' category -- 9,170 GWh/year of geothermal projects and 2,741 GWh/year of hydropower (Logadottir and Lee, unpublished, citing Rammaaaetlum). These 'possible builds' equal roughly two-thirds the capacity which exists or was under construction as of 2011 (Ibid). An open consultation period followed (Rammaaaetlum, Undated). Additional review remains outstanding for less than a third of the projects (Logadottir and Lee, unpublished, citing Rammaaaetlum). Nonetheless, the onus is with Parliament to approve the next stage of development.

While the Master Plan is an atypical and multi-faceted step in Iceland to address energy development with integrated planning, it has received some criticism for (1) using poor

[17] The Plan carried similar scoping to a Strategic Environmental Assessment in that it evaluated prospective energy options at a level beyond a single project. However, it also differed by not covering cumulative or higher order effects (Thorhallsdottir, 2007a and 2007b).

quality information to determine energy, tourism and environmental values; and (2) lack of consideration given to alternative scenarios (Logadottir and Lee, unpublished). Yet, the Master Plan process is also viewed as a way to engage society, albeit imperfectly, in difficult choices about tradeoffs associated with energy, the environment, economics and societal values (Interviews, 2011-2012). Notably, no explicit guidance was offered in the Master Plan outcomes regarding a desirable pace of project adoption or patterns of ownership (Logadottir and Lee, unpublished).

Another major environmental development of relevance was the ratification of the Kyoto Protocol in Iceland in 2002. In conjunction with this, Iceland was granted an allowance for unusual circumstances. Basically, Iceland had already eliminated most fossil fuels from its heating and electricity prior to 1990, the Kyoto benchmark year, so Iceland's base value for emissions would be set at 110% of the 1990 amount (Valfells, et al, 2004, citing UNFCCC, COP3). Still another unusual aspect of Iceland's GHG emissions was that they were also closely linked to foreign companies' manufacturing activity on domestic soil. This issue would be addressed in a separate addendum arrangement, 14/CP.7 of the Framework Convention on Climate Change in which heavy industry emissions were delineated on a separate line from the country's total, if best technology and environmental practices were employed (UNFCCC, 2001; Valfells et al, 2004).

Changes in public response to hydropower projects signaled a potential shift in the energy landscape for geothermal energy. In short, the Karahnukavirkjun hydropower project, built by Landsvirkjun to provide power for aluminum producer Alcoa, spurred large demonstrations and debate on the future of Iceland's energy pathway. Proponents of the project argued it would bring jobs and improve the area economy, while opponents contended it would destroy pristine wilderness.[18] While the hydropower project is now operational, it showed that the least costly power option may not be as favorable or easily installed going forward.

In other areas of environmental-economic note, the 2005 Stern Report on the economics of climate change called attention to Iceland's status as the largest producer of (primary) aluminum in the world on a per capita basis, indicating:

> The near-future looks set to see a continuing sharp increase in aluminium production in Iceland ... making Iceland the largest aluminium producer in western Europe.... Emissions of CO_2 from electricity production per capita in Iceland is the lowest in the OECD.... Iceland is also taking action to reduce emissions of fluorinated compounds associated with aluminium smelting. Expectations of future globalisation action to mitigate GHG (greenhouse gases) emissions is already acting as a key driver in attracting investment of energy-intensive sectors away from high GHG energy suppliers and towards countries with renewable energy sources (2005).

Juxtaposing Stern's observation and elements of the public debate over Karahnukavirkjun, one finds an environmental tradeoff in the gains made globally with reductions of GHGs through clean, Icelandic energy versus local gains from the conservation of Icelandic resources.

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[18] This Eastern Iceland project had been rejected by the Icelandic Planning Authority on grounds that the environmental impacts were significant, but it was nonetheless approved later by the Ministry of the Environment (Interview, 2012). Construction began in 2003 on five dams (690 MW, rated output 115 MW) designed to produce approximately 4,600 GWh annually to power an Alcoa aluminum smelter plant (Landsvirkjun, Undated). Based on interviews and reporting, the project was highly controversial and encountered considerable opposition, from both domestic and international opponents (Petursson, 2008; Johannesson et al, 2011; Interviews, 2011-2012).

While questions related to the above tradeoff linger, the playing field continued to evolve with institutional changes. The NEA was split into two organizations with (1) the Iceland Geosurvey (ISOR) responsible for science and technical consulting and (2) the NEA responsible for monitoring and licensing geothermal resources, serving as the independent regulator for the electricity market, and advising the government on energy issues, among other functions (National Energy Authority Act No. 87/2003; Electricity Act, No 65/2003; Act on Survey and Utilization of Ground Resources No. 57/1998; Interviews, 2011).

An international deep drilling project (IDDP) also commenced with Icelandic companies and the NEA leading a partnership focused on testing the economic feasibility of hydrothermal systems of geothermal resources at depths of 4 to 5 kilometers and 400-500° C (supercritical conditions) (Ibid; Valfells et al, 2004). Advanced drilling technology was used with new fluid management (Valfells et al, 2004). If successful, the approach could reduce the environmental footprint of geothermal production activities as well as substantially increase geothermal potential (Ibid). In 2009, drilling was terminated when the project penetrated molten rock (Fridleifsson et al, 2010). IDDP plans to continue drilling in other regions and, as of 2010, was seeking additional funding (Ibid).

Iceland's power market underwent a transition to competition beginning in 2003 with Electricity Act, No 65/2003 (based on EU Dir No 96/92 and Dir 54/EC) and the Act on the establishment of Landsnet hf, No 75/2004, and Competition Act No. 44/2005. The market was fully opened to competition in 2006 with third party access to transmission and distribution (Ibid). Public utilities remained among the major players [19] and the wholesale market is dominated by public company Landsvirkjun which produced 73% of the power in 2010 (Olafsson et al, 2011).[20]

One effort to privatize a state-owned energy company brought questions about governance of natural resource into prominent view. What is now HS Orka was formed from a decoupling of Hitaveita Sudurnesja (HS). Through a sequence of acquisitions, Canadian-owned Magma Energy (via its Swedish subsidiary) now holds 66.6% and Jardvarmi, a pool of Icelandic pension funds, holds 33.4% (HS Orka, 2012). However at one point in the privitization, Magma Energy held 98.5% of HS Orka, leading to a major public outcry over foreign control of Icelandic resources (Interviews, 2011). This spawned a governmental review of H.S Orka's acquisition process with the possibility of

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[19] Landsnet is the public grid operator, formed as a spinoff of Landsvirkjun's holdings. There are 6 distribution companies, all but one owned by either the State or municipalities (Olafsson et al, 2011). RARIK, the Icelandic State Electricity Company is the largest (Logadottir and Lee, unpublished).

Key companies operating in geothermal power include:

- Landsvirkjun, owned by the State, produces electricity and holds 63.2 MWe;
- Reykjavik Energy, owned by municipalities of Reykjavik, Akranes, and Borgarbyggd, produces and distributes water and power from two cogeneration plants (423 MW_e and 430 MW_t) and 750 MW_t from a number of geothermal areas;
- HS Orka, formed from the privatization and splitting of Hitaveita Sudurnesja, generates heat and power from 150 MW_t and 176.4 MW_e (Olafsson et al, 2011; Logadottir and Lee, unpublished; Landsvirkjun, Undated).
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[20] Some rules were modified subsequently for example, Act 58/2008, which required CHP plants to maintain separate accounts for power and heating (Steinsdottir et al, 2009).

re-claiming ownership (an act that would have had international ramifications, given the EEA agreement that was in place). The review found that Magma Energy was in full compliance with Icelandic law (PR Newswire, 2011) and ownership has since been diluted with increased ownership by Icelandic pension funds.

Additional developments having relevance for geothermal energy included: a banking crisis, a 'greener' change of government, and Landsvirkjun adapting to the competitive market. In 2008, Iceland's banking sector collapsed after an international liquidity crisis exposed the overleveraged status of Icelandic banks (Logadottir and Lee, unpublished; CIA, 2012). Currency depreciation, unemployment, and economic recovery measures led to a state takeover of the banking system and loans from the IMF and other countries (Ibid). This crisis distracted public attention and affected energy project economics (Interviews, 2011-2012). Changes in the government in 2009 leading to a Left-Green and Social Democratic alliance placed 'green development' on more favorable footing. Yet, the ramifications of the banking collapse counterbalanced some of the advantages of a greener playing field (Ibid). A committee was also formed in 2009 to advise on the development of a comprehensive energy policy and has since put forward recommendations (NEA, Undated). These recommendations, like the Master Plan findings, are under review. Finally, Landsvirkjun is evolving with the new, competitive environment. Under a new Chief Executive Officer, Landsvirkjun has demonstrated greater transparency, including publishing (in a rare move) its current electricity price for heavy industry (Reitun, 2010; Landsvirkjun, 2011, see Appendix). The company has reevaluated its strategy and engaged in high level discussions about potential for the subsea cable as carbon reduction targets and favorable economics make this option newly viable (Interview, 2012; BBC, 2012). If the subsea cable project were to move forward, Iceland's energy options could broaden considerably.

Overall, large-scale investment by heavy industry which began again in the latter half of the 1990s, spurred growth in Iceland's geothermal-based power generation, increasing geothermal energy's share of Icelandic electricity from 10% in 1998 to 26% in 2010 (IEA, 2012). Considered more broadly in the context of the total primary energy supply (which includes power, heating and transport, etc), geothermal energy's share rose from 52% to 65% (Ibid). Finally, the share of the population covered by geothermal-based district heating ended the period at roughly 90% (NEA, 2012).

D. INNOVATIONS and ADAPTATIONS

Among the important innovations and adaptations in Icelandic's energy transition, were:

- **Technology:**
  - Improved exploration and standard drilling
  - Site engineering and process redesign
  - Deep drilling
- **Resource parks and industry spillovers**

Exploration and Standard Drilling

In certain regions of Iceland, geothermal resources lie near the surface, whereas in other parts of the country, the resources are situated at depths of 1,000 to 2,000+ meters below the surface. To find such resources in ways that are suitable for economical exploitation, exploration has been improved with enhancements in prediction and drilling methods as well as in the use of special drilling rigs (Interview, 2012).

In the low temperature sector, advances were made in exploration with structural geology methods; resistivity surveys; and shallow temperature gradient holes, which have enabled discoveries of hot temperature geothermal reservoirs that have limited surface-level indications (Communications with S. Bjornsson, 2012). Improved structural geology methods, for example, have assisted with the prediction of fracture system geometry and the dynamics of potential fluid flows, allowing a more fitted stimulation of a geothermal reservoir (Phillip et al, 2007). Progress was also evident in the development of down-hole pumps, which facilitated increases in production by a factor of 10 (possibly an order of magnitude larger), relative to the free-flow from wells (Communications with S. Bjornsson, 2012; Axelsson et al, 2010, citing Axelsson and Gunnlaugsson, 2000).

In the high temperature geothermal sector, progress has also been made with exploration and drilling methods. Exploration techniques, specifically with transient electromagnetic rand magnetotelluric resistivity, microearthquakes, and geochemical thermometers have aided in the identification of targeted drilling areas in high temperature fields (Communications with S. Bjornsson, 2012). The use of transient electromagnetic resistivity methods, for instance, allows for the analysis of sub-surface resistivity structures by sending an artificially induced alternating current into the earth (Hersir and Bjornsson, A., 1991).

Changes with directional drilling have allowed additional improvements in geothermal development. Basically, this technique allows multiple holes to be drilled from the same drill pad. Its enhances the ability to manage the direction of drill holes that would intersect with faults and fractures (Communications with S. Bjornsson, 2012; Interviews, 2011-2012). Such techniques improved the success ratio of wells, where the average yield per drilled well is now about 5 MW_e with some wells yielding as much as 20 MW_e (Communications with S. Bjornsson, 2012). While full data to evaluate the increased efficiency is not readily available, the techniques are widely recognized by industry and researchers for having substantially reduced drilling risk - a critical cost factor in geothermal development (Ibid; Interviews, 2011-2012).

Site Engineering and Process Design

In addition to exploration and standard drilling advances, countless adaptations have been made to improve the harnessing of geothermal resources, many of which are site-specific. An example, noted earlier, was in the development of heat exchange methods and plant design which allowed the utilization of the high temperature fluid for the Svartsengi plant. In that particular case, the high salinity of the fluid and large amounts of minerals precluded direct use. Integration of a heat exchanger to warm a secondary fluid provided a means to overcome many of the issues. Other improvements with scaling and corrosion inhibitors, return water re-injection, and system efficiency enhancements addressed site-specific challenges related to scaling and corrosion, sea water incursion, and overexploitation, among others (Axelsson et al, 2010). Additional gains were made with improved pipe insulation of district heating systems (Interview, 2012).

One particular case worth highlighting involves process redesign and repowering. The Svartsengi plant, for instance, uses high temperature geothermal energy to produce heat and electricity. The geothermal fluid is rich in minerals with a high salinity level (roughly 2/3 of that in sea water) which can be corrosive. For Svartsengi geothermal energy use in the 1970s, NEA scientists developed a dual flash plant design which heated ground water through a heat exchanger (HS Orka, 2012; Interview, 2012; Albertsson et al, 2010). In subsequent adaptations, re-design utilized the plant's waste stream to produce an additional 8.4 MW of power, more than doubling its installed power output (Kaplan and Schochet, 2000). .

Deep Drilling

Deep drilling for geothermal energy represents another kind of adaptation which has emerged mostly in the past decade in conjunction with the IDDP project. Opportunities for studying and testing depths of 4 to 5 kilometers and super-critical conditions of 400-600 °C with this project presented unusual conditions for technological and procedural adaptation (Interviews, 2011-2012; Fridleifsson et al, 2010; Fridleifsson and Elders, 2007). While holding vast potential, this area remains still emergent and one to watch.

Resource Parks and Geothermal Application Spillovers

The adaptation of geothermal energy for uses which go beyond space heating and power reflects a major area where Icelandic innovation has occurred.

Building on the earlier example with the Svartsegi plant, effluent fluid from the plant is used in the neighboring Blue Lagoon spa and health center. This area has become a major travel destination for tourism, in addition to spillovers in health industries, cosmetics and microbial R&D that have developed around the geothermal resource (Gudmundsdottir et al, 2010; Albertsson and Jonsson, 2010a and 2010b; Interviews, 2011-2012; Blue Lagoon, Undated). Such multi-industry development reflects what is sometimes referred to as a 'resource park' where resource utilization is done in an integrated and sustainable way (Albertsson and Jonsson, 2010a; Interviews, 2011-2012).

Another spillover application of geothermal energy is in fish farming (NEA, 2012, Interview, 2012). It is generally understood that young salmon and trout grow more rapidly in temperatures of 10-12°C relative to the average ground water temperature of 4°C found in Iceland (Interview, 2012). Based on this insight, warm water, like that from boreholes, has been used for decades for salmon and trout breeding practices (Ibid). One unusual case even utilized warm effluent water from an aluminum plant at

Straumsvik (Ibid). Gains were apparent in the 1980s with increases in fish farming that utilized geothermal heat mostly through heat exchangers (NEA, 2012; Ibid).

Yet another spillover application of geothermal energy is to melt snow and de-ice roads, parking areas, and walkways in areas with geothermal district heating (Loftsdottir and Thorarinsdottir, 2006; NEA, 2012). Employed in recent decades, this process utilizes systems installed under target areas that channel geothermal water from space heating.

Sectoral Contributions

Sectoral contributions for the above innovations and adaptations are outlined below. Relative influences, as gauged with other cases in this study, are derived from the interview feedback, historical reporting, and case analysis. Weighting is indicated by the number of squares per category.

Table D1: Sectoral Contributions to Innovation/Adaptations

Innovation/Adaptation	National Government	Industry	Civil Society	Other (Academia, NGOs, etc)
Technology				
• Exploration and 'Standard Drilling'	■■■	■■■	■	■■■
• Site engineering and process re-design	■	■■■		■■■
• Deep Drilling	■■	■■■		■■■
Resource Parks and Industry Spillovers				
• Spa, health, R&D parks		■■■	■■	
• Fish farming		■■■		
• De-icing systems		■■■	■■■	

**Note: As energy companies are state and/or municipality owned, their contributions can appear under National Government, Industry and Civil Society (where municipalities are included). Work done by the NEA, ISOR, and the formerly state-owned drilling company falls under National Government, Industry and Other.*

From this summary table, industry stands out as the most wide-ranging and substantial contributor across all adaptations. It bears noting that industry actors were also typically public energy companies. In the government sphere, the NEA/ISOR and the state-owned drilling company have been critical to exploration, drilling and plant design/redesign, in addition to related work of the state-owned power company. The role of civil society is more passively evident in use of spillovers, like spas, and through active municipal engagement in exploration and drilling. Notably, municipality involvement includes not only municipally-owned energy companies, but the initiation of resource studies and tests done by, for example, the NEA/ISOR and drilling companies. The degree to which municipalities have been engaged appears to be varied over time and is a useful point of departure for further study.

E. KEY DRIVERS and BARRIERS

Based on analysis of interview feedback, historical records, and other data, the following reflects the main determinants of Iceland's geothermal energy transition.

Drivers

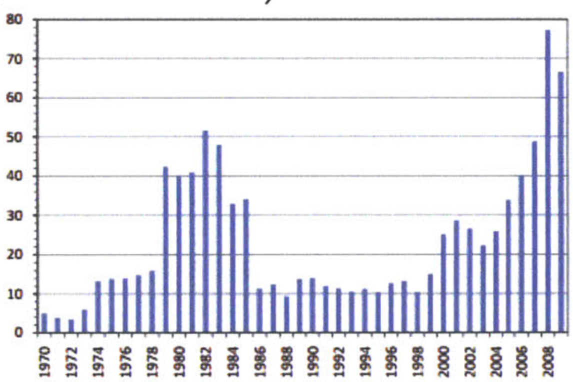
- **Reduction of Oil Imports/Balance of Payment Savings**
- **Growth of Energy-intensive Industry**
- **Rising Socio-economic Development**
- **Environmental Concerns**

Reduction of Oil Imports/Improvement of Balance of Payments

Like the other countries discussed in this study, Iceland adopted an explicit transition strategy around the time of the oil shocks in order to displace oil. Geothermal energy was already a fairly common energy source in some areas, so the national government, municipalities, and energy companies focused on expanding and/or modifying infrastructure to eliminate imported fuels from space heating (Ministry of Environment, 2010, Interviews, 2011-2012).

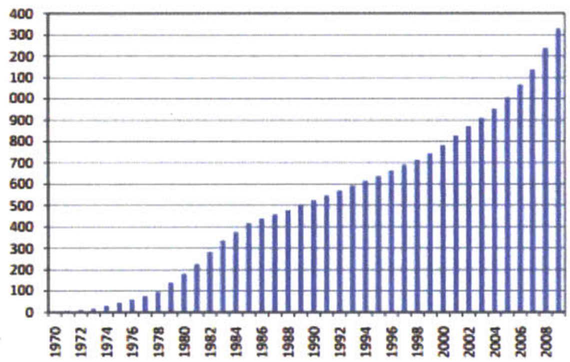
The Icelandic National Energy Authority analyzed savings from the use of geothermal energy in lieu of imported oil for heating in the period 1970-2009. Figure E1 shows annual savings ranging from 3.42-77.33 billion ISK per year ($26-600 million, 2010) with substantial costs avoided in the 1970s/early 1980s and in the last decade when oil price increases were at their highest. Figure E2 consolidates this information, showing cumulative gains of 1,330 billion ISK ($10.2 billion, 2010 net present value). This subject is covered in more depth later, as it pertains to import dependence.

Figure E1: Annual Savings from Use of Geothermal Energy in lieu of Oil in Heating *(Billions krona, based on prices in June 2010)*



Source: Haraldsson et al, 2010.

Figure E2: Cumulative Savings from Use of Geothermal Energy in lieu of Oil in Heating *(Billions krona, based on prices in June 2010, net present value)*



Source: Haraldsson et al, 2010.

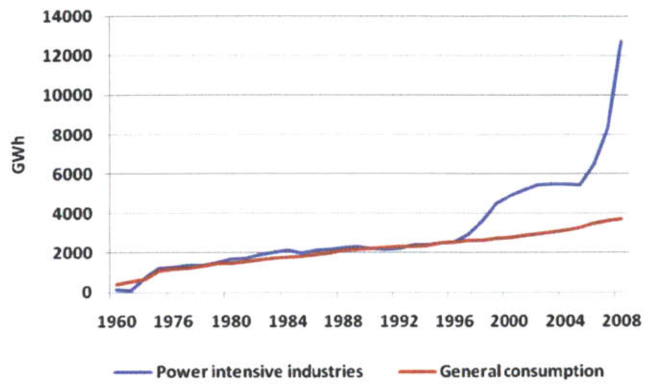
Growth in Energy-intensive Industry

Since the 1960s, the Icelandic national government and domestic energy companies have pursued an energy-industrial strategy (to varying degrees) designed to attract foreign investment in a manner which utilizes Iceland's hydropower and geothermal power. One estimate of economic gains from this indicates that energy-intensive industry contributed on average to about 0.5% of the annual GDP between 1969 and 1997 (Valfells et al, 2004).

From the standpoint of the domestic energy companies, developing heavy industry power projects with foreign companies that base subsidiaries in Iceland can be highly attractive. This favorability exists because the capacity of a power plant can be fully utilized from the point of operational start-up with a heavy industry customer (Interview, 2012). By contrast, the use of geothermal energy for residential heating requires time for the market to 'grow into' the capacity of a plant (Ibid).

Figure E3 shows the rapid growth of electricity consumption by heavy industry since the late 1990s. In line with major investment in aluminum smelting that commenced around 1997, a sharp increase in power use is evident. Due to the small nature of the power sector, new power plants are generally not pursued until power purchases are guaranteed (Ministry of the Environment, 2010). This may be due in part to public criticism in the 1980s over a hydropower plant that was built well in advance of new demand (Landsvirkjun, 2009).

Figure E3: Electricity Consumption in Iceland



Source: Ministry of Environment, 2010.

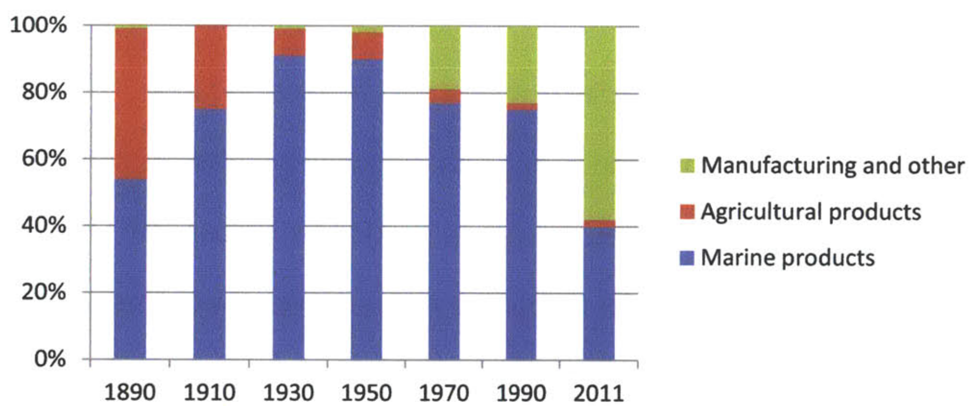
Specific to energy-intensive industry, new projects and project expansion have encouraged the build-out of Icelandic installed generation. For example, the Century Aluminum smelter, which opened in 1998, has more than quadrupled its capacity, now producing 260,000 tons of aluminum per year (Ibid). The Alcoa smelter that came on-line in 2007 has the capacity to produce 350,000 tons of aluminum per year (Ibid). Even the first aluminum smelter that opened in 1970 (now owned by Rio Tinto Alcan) produces 180,000 tons of aluminum per year -- 6 times more than when it started (Ibid). In other areas of heavy industry, the Elkem ferrosilicon plant that opened in 1979 currently produces double its original capacity, now at 120,000 tons of 75% ferrosilicon (Ibid). This growth in heavy industry is not inconsequential. Overall power generation for heavy industry equaled 77% of the total electricity produced in Iceland in 2008 (Ibid).

Rising Socio-economic Development

Tied to the above discussion of increased heavy industry is continued socio-economic development. Iceland underwent a very substantial change in its socio-economic status in the 20th century accompanied by increased use of energy. Whether one views energy demand as driving growth or as a result of it, geothermal energy is now the most used fuel in the total primary energy supply (see Energy Mix section).

Looking at the economic structure in Figure E4, a major shift can be seen moving away from agriculture at the turn of the 20th century toward manufacturing.

Figure E4: Exports by Commodity *(Value as a Share of Total Exports)*

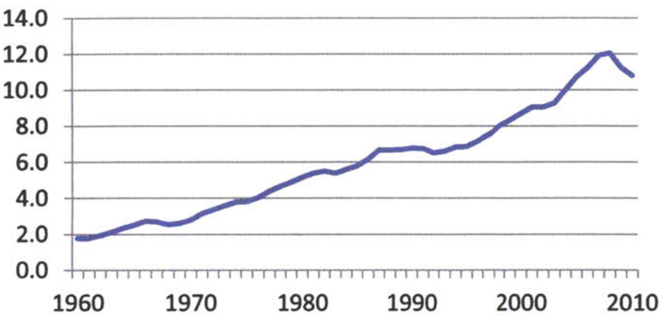


Source: Statistics Iceland data, 2012. Note: Value is free on board which means the price on board by whatever means of transport. Some rounding applies.

This restructuring entailed increased energy use and was rooted in a broadly recognized effort to diversify and expand the domestic economy (Interviews, 2011-2012; Landsvirkjun, 2009; Ingimarsson, 1996; Einarsson, 1991).

In line with diversification, a dramatic rise in gross domestic product can also be seen in the period between 1970 and the present (Figure E5).

Figure E5: Gross Domestic Product, Iceland *(Billion in constant US$, 2000)*



Source: WDI data, 2012.

On an average annual basis, GDP rose 7% while GDP per capita increased 4%, both in constant US$, 2000 (WDI, 2012).[21] Considered in terms of final household consumption per capita (constant US$, 2000), growth for the period studied was 51% (WDI, 2012). These changes track directionally with broad trends in energy use.

The changes detailed above tie to another major shift evident in Iceland -- the improvements in the quality of life. For the period between 1980 and 2011, Iceland evidenced a clear increase in life expectancy, access to knowledge, and standard of living (Table E1).[22]

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[21] The difference in rates is associated essentially with a population increase of more than 56% for the same period (Statistics Iceland, 2012).

Population data is based on data for January 1 of each year. For the broader period of 1900 and 2012, population increased by more than a factor of 4 (Statistics Iceland, 2012).

[22] This time range accounts for changes in methodology and underlying data (UNDP, 2012).

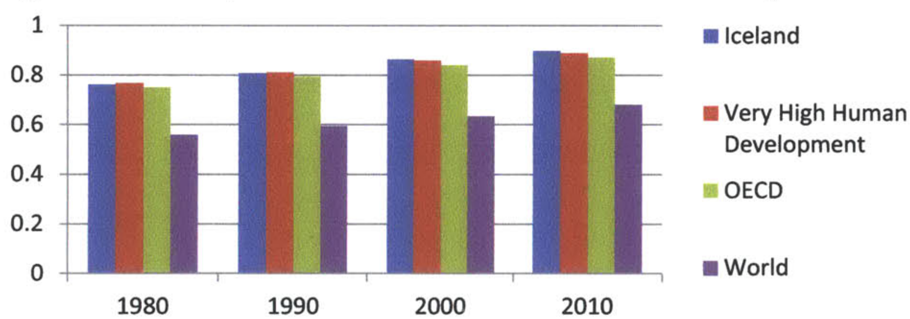
Table E1: Iceland Profile

	Life Expectancy at birth	Expected Years of Schooling	Means Years of Schooling	GNI per Capita (2005, ppp$)	HDI Value
1980	76.6	12.5	7.4	21,440	0.762
2011	81.8	18.0	10.4	29,354	0.898
Change	7%	44%	41%	37%	18%

Source: UNDP data, 2012.

To gain some context for these changes relative to other countries, Figure E6 compares the Icelandic performance relative to peer countries in the Very High Human Development group, OECD and World for certain years in the past few decades. Not only did Iceland start more highly positioned (a major change from its status in the early 1900s), but it grew and exceeded the other classes of country groups in 2000 and 2010.

Figure E6: Comparative Trends in the Human Development Index



Source: UNDP data, 2012.

While this data shows a change in the standard of living, it does not indicate a direct causal link between energy use and improved standards of living. Interviewees, however, regularly noted such linkages (2011-2012). While beyond the scope of this study, this area provides interesting opportunity for further research.

Environmental Concerns

Environmental concerns served as both drivers of and barriers to the expansion of geothermal energy in Iceland. On the positive side, smoke free air was an observed benefit in the shift toward geothermal energy from oil/coal in heating. Deemed a 'smokeless city,' Reykjavik has come a long way from its more polluted state in the 1940s (Arnorsson, 1975; NEA, 2010; Figure E7).

Figure E7: Reykjavik in the 1930s with a cloud of smoke, attributed to coal heating.

Source: Bjornsson, S., 2010, referencing Thordarson, 1998.

As for environmental challenges, geothermal waste water must be disposed of in a manner which does pollute ground water.[23] The 303 MWe Hellisheidi plant, for example, utilizes roughly 600 kg/s of steam with the remaining geothermal fluid of at least 1,000 kg/s waste water plus roughly 400 kg/s of condensed water requiring re-injection (Communications with S. Bjornsson, 2012). Reinjection at this site has induced seismic

[23] Flash plants use roughly 20-40% of the mass of geothermal fluid, so the rest of the fluid plus the condensed water from the turbine must be managed with re-injection (Communications with S. Bjornsson, 2012).

activity with earthquakes up to a magnitude of 4, creating anxiety in the Hveragedi village (Ibid). Reinjection, earthquakes and related releases of H_2S are environmental issues which require effective address for future development.

Considering the environment from a different level, views on nature preservation and conservation in relation to energy have been articulated over the earlier years (Ibid; Olafsson, 1981; Magason, 2008). Yet in the late 1990s and 2000s, concerns about the direction that Iceland was headed with its commitment to heavy industry and the effects such reliance would have on the environment became increasingly pronounced (Interview, 2012). Intersecting with this has been heightened international attention on climate change (IEA, 2011; IPCC, 2007) with GHG reduction targets spurring energy-intensive industries to seek sites, like Iceland, where they could relocate their operations and leverage cleaner energy.

Domestically, the Master Planning process has shown geothermal projects to be 'more acceptable' than alternatives. Deep-seated societal discontent with recent hydropower development appears to have solidified this point. Currently, a prevailing view among interviewees is that large-scale hydropower projects will be unable to pass a vetting process for the near-term (Interviews, 2012). If true, energy development would likely follow a geothermal route.

Barriers

- **Geological Conditions/Time Needed to Explore/Step-wise Adoption/Uncertainty**
- **Costs**
- **Monopoly of National Power Company**
- **Environmental Concerns**

Geological Conditions/Time to Explore /Step-wise Adoption/Uncertainty

The technology profile of a geothermal resource has some aspects which can be viewed as unfavorable relative to the competing (Icelandic) alternative found in hydropower. Geothermal energy is generally more uncertain in terms of the amount of the actual resource available and its sustainability hinges on stepwise approach (Interviews, 2011-2012; Islandbanki, 2012). As former, NEA scientist Stefan Arnorsson (1975) noted, geothermal utilization requires "more elaborate technical and costly research in the early phase of economic evaluation," including geological assessments and drilling. If all other project aspects were equal, these technology characteristics of geothermal energy suggest that hydropower could be a better candidate for increased energy production.

Costs and Financing

Costs served as a barrier to geothermal adoption in the power sector, principally for large projects (not incremental CHP). In power plant investment decision-making for Iceland, hydropower traditionally appears to have had lower investment costs than geothermal energy (Interviews, 2011-2012; see discussion of costs in the Change

Indicator section). While much of the cost/pricing information in Iceland is protected by law and/or confidentiality associated with long-term contracts, one recent and credible estimate indicates geothermal energy costs are $2,500/kW versus hydropower at $2,200-2,300/kW (Steering Committee for Comprehensive Energy Policy, 2011, citing Mannvit, 2011). Combining insular market economics with the drilling uncertainty of geothermal energy resources, noted earlier, and the investment profiles of hydropower and geothermal energy (i.e. no fuel costs), one finds that Icelandic hydropower has been viewed more favorably for large scale-up. Importantly, this does not take account of the Master Plan findings, other societal concerns, policy changes or larger shifts in the market, such as what might be achieved with a subsea cable.

With respect to financing, geothermal projects inherently are challenged by the uncertainty of their risk profile plus the front-loaded nature of investment costs. According to a report by Islandbanki, an Icelandic bank which specializes in geothermal finance, debt financing can typically cover about 60% of financing for research, development, and drilling. The remaining 40% must be covered by equity (2010). For the Icelandic energy companies that are publically as well privately-owned, sources of public funds have been heavily constrained after the recent banking crisis. When combined with a weakened Icelandic currency, conditions for geothermal energy-based companies reflect heavy challenges for raising necessary equity in an already complicated risk and financing landscape (Islandsbanki, 2010)

Monopoly of the National Power Company Landsvirkjun

The monopoly held by Landsvirkjun was highlighted in interviews as another barrier to the scale-up of geothermal energy in the Icelandic power sector (2011-2012). Essentially Landsvirkjun, through its governmentally-mandated charter and early mover status, had first claim on the power market until the market was opened to competition with the 2003 Act. Landsvirkjun and Reykjavik Energy remain publically-owned, yet other market entrants can now compete.

It is worth noting, here, that early charters for other companies, like HS Orka's predecessor, were structured with mandates focused on heating/hot water services. Such a company's ability to sell electricity (even if produced efficiently in a CHP capacity) was limited until the charter was expanded by the parliament (Interview, 2012).

Environmental Concerns

(This determinant is a driver and a barrier. See under Drivers.)

F. CLASSIFYING CHANGE

Iceland's geothermal transition for the period 1970 to the present followed three tracks.

With heating, particularly space heating, the transition was hybridized, stemming from bottom-up and top-down impetuses. After the first oil shock, there was a clear and concerted effort to accelerate a more comprehensive shift away from oil to geothermal energy by municipalities, the national government, and public actors NEA/ISOR, Landsvirkjun, Reykjavik Energy, and Hitaveita Sudurnesja (now privately owned HS Orka). Since local authorities are classified among bottom-up interests, they serve to balance some of the top-down influences, constituting a hybridized change.

A second track of energy change was tied to heavy industry's use of power. Here, the national government's long-term promotional efforts (through various public agents), in conjunction with industry efforts, spurred development that was met by industry. This reflected a top-down led hybridized change.

A third track, which centered on combined heat and power, was led by industry. Here, process and technical adaptations were made, creating CHP plants, to more efficiently tap geothermal energy for power generation. This was a more bottom-up led hybridized change.

The three geothermal trajectories, described above, differ from what spurred the earlier transition at the beginning of the 20th century. At that time, entrepreneurial homeowners and farmers drove change in the area of heating, not unlike the bottom-up change evident with mobilizers in the Danish wind transition of the 1970s (Chapter 5).

Turning to the way in which the national government fostered the geothermal energy change, a range of methods were evident. Deployment was largely effectuated by public industry agents Landsvirkjun, Reykjavik Energy, Hitaveita Sudurnesja carrying out the extension of infrastructure and markets, as well as in harnessing new resources. Incentives were used, principally in the form of loans for exploration/drilling. Information also proved to be important through the provision of resource assessments by the NEA and active international solicitation of contracts by the Ministry of Industry-Landsvirkjun marketing office.

What was the pace and extent of energy substitution? Displacement of fuels in the power sector by geothermal energy was limited and slow until the late 1990s at which point geothermal energy scaled quickly to a critical, but not majority share (see Energy mix section). Greater change in the period that was studied was found in the heating sector. Here, the existing energy transition accelerated rapidly with the oil shocks of Stage 1, and then essentially maintained at a constant status in Stage 2 and 3.

Finally, when considering the form of technology change, some distinctions can be drawn. Improvements with the use of down-hole pumps and plant redesigns appear to have been significant. Other changes, like that of improved drilling and resource evaluation methods are locally understood among practitioners and researchers to have provided gains. At this juncture it is unclear, if they are incremental or radical in nature. Robust adaptations are also evident in the build-out of spillovers into fish farming, snow melting, spas and health care with the resource parks.

G. CHANGE INDICATORS

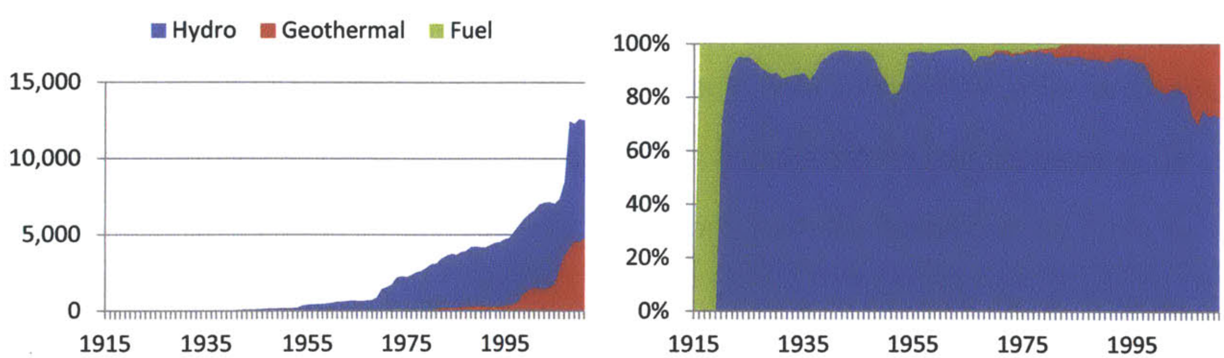
The effectiveness of the Icelandic geothermal energy transition, as with the other cases, is examined in terms of the energy mix, costs, societal acceptance and industrial development.

Energy mix/balance

There are a number of ways to consider the transition in the energy mix in Iceland specific to electricity, heating and the total energy balance. Data are exceptionally strong in certain aspects of this country case, so fuller scales are included.

Figures G1 and G2 reflect Iceland's fuel use in electricity on a unit and relative share basis for nearly 100 years. As shown, electricity use began with fossil fuel, namely oil and coal imports, then rapidly shifted to hydropower and eventually added geothermal in the late 20th century.

Figure G1 and G2: Fuels Used in Electricity Production, 1915-2011
(GWh and Relative Shares, respectively)

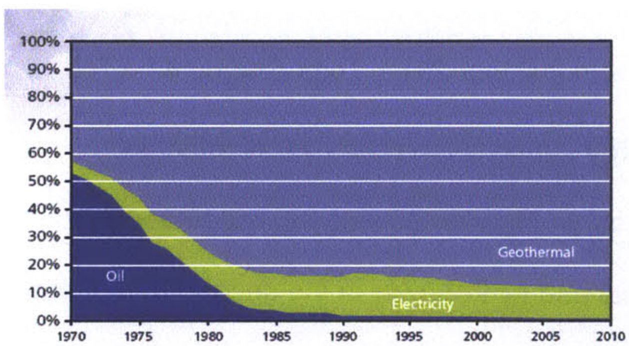


Source: NEA, 2012 for both.

Specific to the period of this study, the geothermal intensity or the share of geothermal energy in total power increased from 1% to 26% between 1970 and 2010 – equaling growth of roughly <1% per year on average (IEA, 2012).

In space heating, where more geothermal energy is utilized, Figure G3 shows a relative shift of geothermal energy from roughly 43% in 1970 to 90% in 2010.

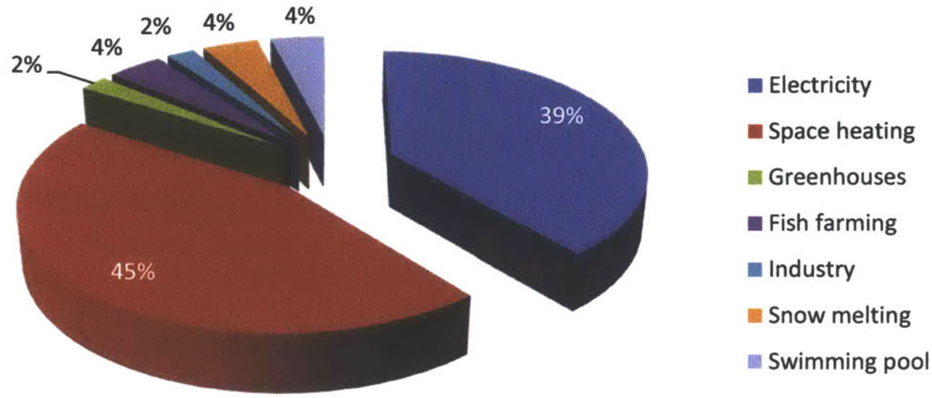
Figure G3: Fuels Used in Space Heating *(Relative Shares)*



Source: NEA, Energy Statistics in Iceland, 2011.

Going a step further, Figure G4 illustrates how geothermal energy is used across applications with space heating and electricity, collectively comprising 84%.

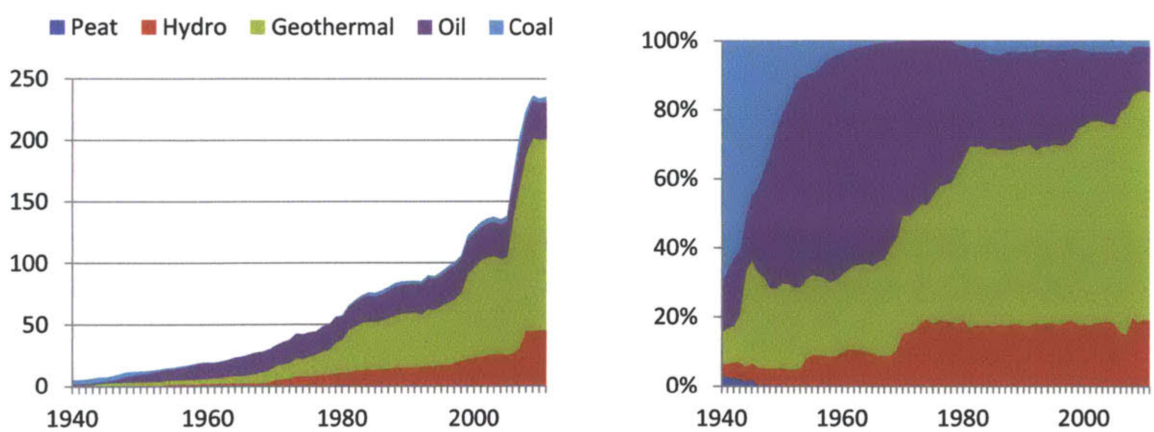
Figure G4: Breakdown of Geothermal Energy Use in Iceland *(2010)*



Source: Adapted from NEA, Energy Statistics in Iceland, 2011, Total Energy 41.1 PJ.

At a more macro level, the total primary energy supply shows the overall effect of scaling geothermal energy across applications. In Figures G5 and G6, the major shift from oil and coal at mid-century to geothermal and hydropower in the second half of the century is clear, with geothermal energy contributing to a larger overall change, compared to hydropower.

Figures G5 and G6: Geothermal Energy in the Total Primary Energy Supply, 1940-2011 *(PJ and Relative Shares, respectively)*



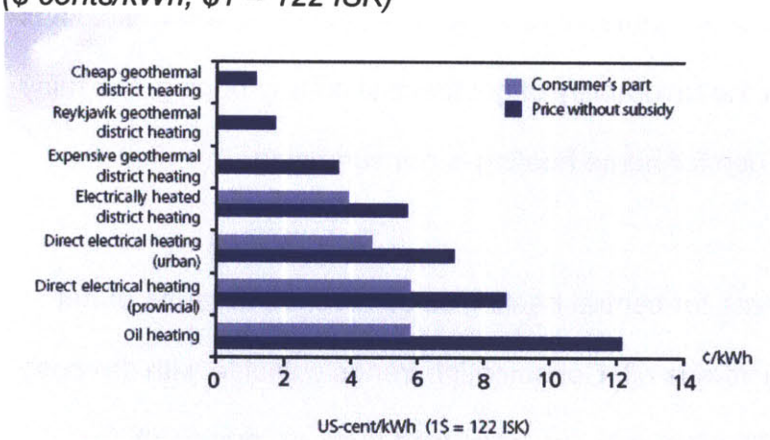
Source: NEA data, 2012. Data for 2011 is estimated.

Costs

Costs for geothermal energy heating were competitive in Iceland in the 1970s and remain so today (Interviews, 2011-2012). Costs for electricity derived from geothermal energy In Iceland were not competitive in the 1970s, but are now (Ibid).

Recent estimates for energy prices in Icelandic residential heating indicate that geothermal heating is the most competitive, as other fuel sources are subsidized to provide equity in cost coverage (Figure G7).

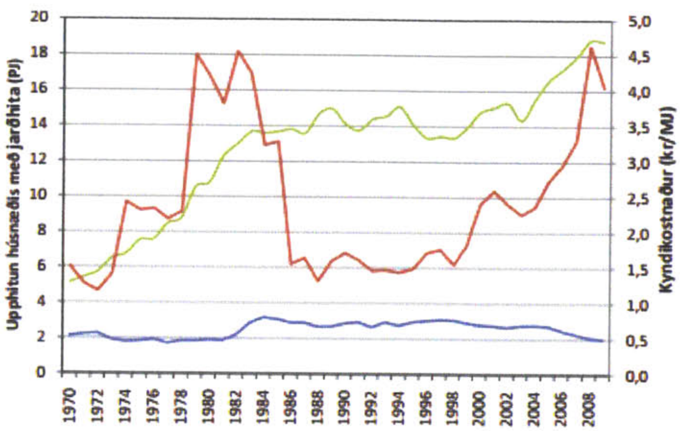
Figure G7: Comparison of costs for heating in Iceland, mid-year 2010
($ cents/kWh, $1 = 122 ISK)



Source: NEA, 2011.

Looking at costs over time, substantial differences between geothermal energy and oil for heating are evident throughout the period studied (Figure G8).

Figure G8: Cost and Use of Geothermal for Heating and Energy Development

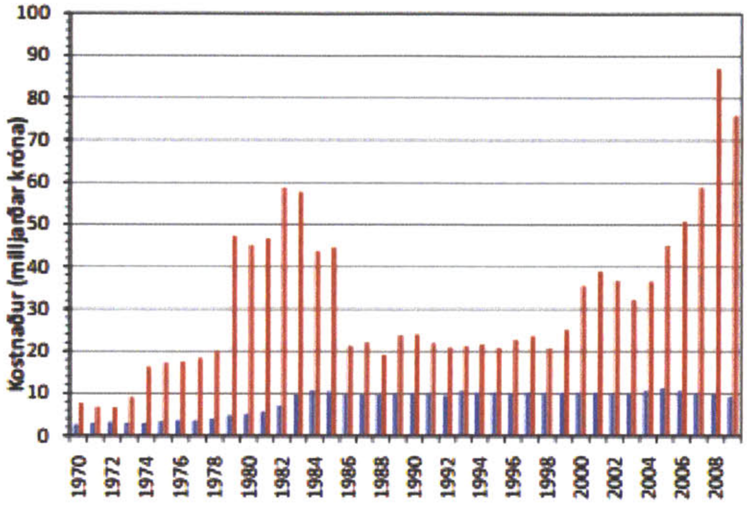


Source: Haraldsson et al, 2010. Note: Green: Home heating w/ geothermal energy Blue: Cost of geothermal heating; Red: Cost of heating with oil

Overall, Figure G8 shows that geothermal energy costs rose slightly during the period, but remain near the lower bounds of the period costs. This contrasts with the radical flux in oil pricing that is evident. Given the favorability of geothermal energy pricing, the fairly steady rise in geothermal energy use for home heating is not surprising.

Finally, Figure G9 highlights patterns for central heating sales revenue in terms of hot water (geothermal energy-based) versus oil. Consumption trends coincide with the cost differential that is evident above. The fact that any oil is used is driven principally by conditions in which some residences are located outside of a network near cold spots, where geothermal heat is not currently accessible.

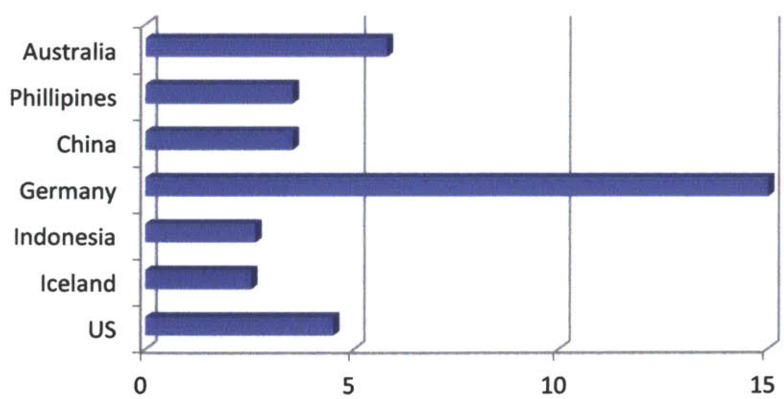
Figure G9: Comparison of Sales Revenue for Central Heating with Hot Water (Geothermal energy) vs. Oil (billions krona, based on prices in June in a given year)



Source: Haraldsson et al, 2010. Note: Blue bars are sales of hot water for space heating; Red bars refer to the oil sales for heating.

Turning to the development of geothermal energy in installed MW across a number of countries utilizing geothermal energy, a study by Islandbanki in 2010 provided estimates showing that Iceland has the lowest development costs – a clear strength (2010) (Figure G10).

Figure G10: Geothermal Development Cost in Select Countries *($/MW)*



Source: Islandbanki Geothermal Research data, 2010.

In terms of electricity, power prices are protected and mostly confidential, yet it is widely understood that geothermal power has become competitive over the period that was studied (Interviews, 2011-2012). Landsvirkjun's new CEO Hordur Arnarson has highlighted the unreasonably low nature of some of the company's contracts in 2011 (Landsvirkjun, 2011; Logadottir and Lee, unpublished). He also emphasized changes in the European electricity market which widened the price difference between electricity sold in Iceland and that in the Continental Europe (Ibid). In doing so, he has articulated a business vision for Landsvirkjun to raise power prices in Iceland in proportion to European price increases (for more detailed discussion, see Logadottir and Lee, unpublished). This, at a minimum, suggests that energy prices and their sustainability are being re-evaluated.

Turning to the question of - who paid? The scale-up in geothermal heating during the 1970s and 1980s was led by the government and municipalities in conjunction with the NEA and the energy companies. This was financed by national and municipality revenue plus customer utility bills. The incremental adoption costs of geothermal power in CHP as well as the robust scale-up with heavy industry were covered by companies and their customers.

A few specifics are worth underscoring. The national government absorbed some debts of district heating for municipalities, following the record inflation in the 1970s and early 1980s together with the collapse of oil prices in 1986 (Interview, 2012, see Energy Overview section on mid 1980s). Additional costs were covered in relation to the restructuring of utilities (Ibid). These costs are separate from those deferred by the Energy Fund that was set up in the 1960s to provide grants and loans with favorable terms for exploration/drilling for geothermal resources (Ibid; Bjornsson, S., 2010). The Fund absorbed some drilling costs, if a project led to failure (i.e. cold or dry wells) (Ibid).

With some degree of competition now occurring in the Icelandic energy field (including large public companies), costs should now generally be passed on to consumers. Historically, heavy industry prices were linked to aluminum profits or aluminum prices, subjecting publically-owned Landsvirkjun and by extension Icelanders to the vagaries of the metals market. Landsvirkjun appears to be making some changes in this regard. In 2010, the company announced a new contract with Rio Tinto Alcan, its second largest client, in which pricing is benchmarked to the United States Consumer Price Index, rather than aluminum prices (Reitun, 2010, see Appendix). The CEO's acknowledgement of some price details (see Appendix) may foreshadow increased transparency to come.

Societal Acceptance, the Environment and Public Health

Broadly, social acceptance of geothermal energy appears to have increased (Interviews, 2011-2012). Some early objections were raised in relation to the visual impacts of pipes and field structures, which appear to have been adapted over time with less overt layouts (Interview, 2011-2012). This can be compared to the visual effects of coal emission clouds which used to linger over Reykjavik, when coal was used more regularly (Gunnlaugsson et al, 2000; Bjornsson, S. 2010).

There are also some concerns related to sulfuric emissions. The release of H_2S has a scent of rotten eggs and may cause some respiratory problems.[24] Increased concentrations of H_2S in the capital area from the Hellisheidi plant have led to demands that H_2S be re-injected (Interview, 2012). Currently, this issue remains open for address and may hinder additional development of geothermal fields near populated regions, until resolved (Ibid).

Another societal concern is one of ensuring that effluents from the geothermal fields do not contaminate ground water. As noted earlier, this is addressed by re-injecting the effluents into the ground, yet can induce seismicity. The issue recently has been an annoyance (Interview, 2012). Given that the island of Iceland is located at one of the most seismic sites in the world, earthquakes must be recognized for their more common nature as well as the danger of inducing them.

Currently, societal acceptance appears to be undergoing some redefinition. Intense discontent associated with hydropower expansion in recent years may leave geothermal energy positively positioned. However, groups within Icelandic society also appear to be questioning the need for additional heavy industry fueled by yet untapped hydropower or geothermal energy (Magnason, 2006; Interviews, 2011-2012). In this regard, heavy industry skews energy consumption currently in Icelandic society (Figure G11).

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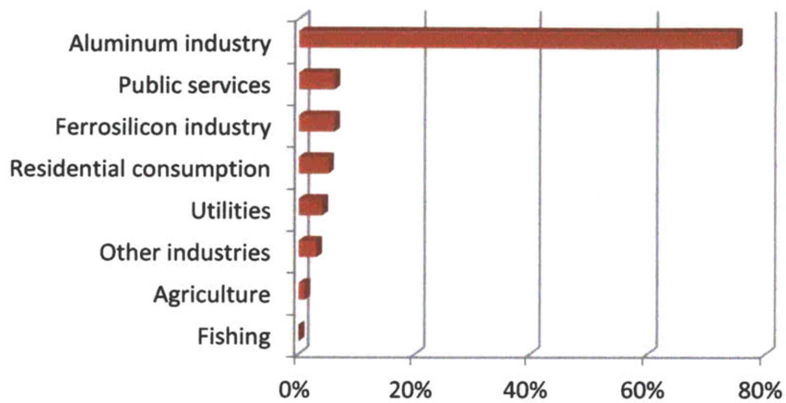
[24] A recent study of Icelandic adults exposed to low levels of geothermal gas releases found asthma-like symptoms which may be associated with the H_2S (Carlson et al, 2012). This subject is still rather new. Interestingly, health changes were noted by Icelandic doctors as far back as the 1950s and 60s indicating a reduction in common colds associated with reduced use of coal furnaces (Jonasson and Thordarson, 2007).

Figure G11: Breakdown of Icelandic Power Consumption in 2010



Source: NEA, 2011.

For the near-term, the banking crisis appears to have distracted public attention from energy and environmental discourse all together (Interviews 2011-2012).

Industrial Development

Industrial development associated with geothermal energy takes a highly varied form.

Iceland's district heating services have a long and proven track record. Reykjavik Energy, including its predecessor, is one of the oldest and largest district heating services in the world (Bjornsson, S., 2006; Loftsdottir and Thorarinsdottir, 2006; Interviews, 2011). Such services emerged in the early 20th century and have undergone numerous changes including market consolidation and expansion, as well infrastructural modernization (Interviews, 2011-2012).

Another area, the utilization of geothermal energy in swimming pools, reaches 138 of the 169 swimming centers in the country (NEA, Undated). The energy and, in some cases, its fluids or minerals are also used for the Blue Lagoon, the Myvatn Nature Baths and Nautholsvík geothermally-heated beach (Ibid).

Fish farming is another important industrial application of geothermal energy and/or its water. Production has gradually grown since 1992, equaling 6,200 tons in 2003, produced by roughly 50 plants (Ibid). Of the output, salmon reflects roughly 70% of the production (Ibid).

Greenhouse use of geothermal energy is one of the oldest forms of its utilization. Geothermal water is employed, for example, to thaw soil in order to harvest produce earlyr in the season (Ibid). An estimated 120,000 m^2 of fields are warmed in this manner (Ibid; Bjornsson, S., 2010; Loftsdottir and Thorarinsdottir, 2006).

Another more recent application of geothermal energy is in the melting of snow or de-icing. This practice increased over the past two decades with the total area of snow melting systems equaling roughly 920,000 m^2 in 2008 (NEA, Undated). Of this, approximately 690,000 m^2 were in Reykjavik (Ibid). Other applications include fish drying; seaweed, salt, and liquid carbon dioxide production, among the varied uses of geothermal energy or its co-products (Ibid).

Going beyond industrial application of geothermal energy, Icelandic expertise in the resource is also widely recognized with respect to consulting and training done by companies, academia, and research centers. In January of 2012, for example, the World Bank and Iceland signed an agreement for Iceland to assist African countries in evaluating and harnessing their indigenous geothermal energy (Iceland Review, 2012). Its UNU Geothermal Training Programme has also produced geothermal experts in Africa, Central America, and Asia. If one looks at international conferences such as the 2010 World Geothermal Congress, approximately 20% of all papers are produced by UNU-GTP alumni (Fridleifsson, 2010; Interview, 2012). Courses from the school are now being offered in locations like Kenya, with more than half the instructors being alumni (Ibid).

In more recent years, companies and related organizations in Iceland's geothermal energy cluster have partnered to enhance their knowledge platform and foster synergies across the group for broader industrial advance (Gekon, 2010; 2012). This includes ongoing data collection and analysis at the cluster level which should offer more means to evaluate this sector in the near-term (Communications with Gekon, 2012).

H. CONCLUSION

Iceland's geothermal transition is a case of cross-sectoral mobilization to scale from an already existing energy transition. The oil shocks spurred the national government and municipalities along with publically-owned energy companies and other state actors to rapidly substitute away from fossil fuels, where possible, in the energy mix. Policy was focused on enabling the transition and was often embodied in the outright deployment measures of public actors.

On balance, the geothermal trajectory in Iceland appears to be well-positioned not only to be sustained, but also to continue on an expanded basis. Such a decision, however, lies with Icelanders' attitudes towards the energy-environmental-industrial-societal nexus and the prospects for connectivity to other markets.

APPENDIX

Iceland's Energy Transition Timeline

Late 19th century

- Experiments geothermal steam in gardening

1899

- Electricity 1st produced in Iceland

Early 20th century

- Geothermal steam applied to heat greenhouses, swimming pools and buildings

1904

- 1st hydropower turbine begins operation

1908

- Stefan Jonsson pipes steam from hot springs to home

1911

- Erlendur Gunnarsson harnesses geothermal energy for heating and cooking

WWI

- Price increases in coal spurred interest in harnessing geothermal energy for space heating and other purposes.

1930

- Large-scale utilization of geothermal energy in space heating begins with a pipeline constructed in Reykjavik

1934

- 38 power stations are in place w/ total installed capacity of approximately 5 MW total (hydropower or kerosene based)

Beginning of WWII

- Imported coal was the key energy source followed by oil; geothermal energy and hydropower equaled about 9.1% of country requirements

1940

- Act on Ownership and Rights of Usage of Geothermal Resources No. 98/1940

1943

- 1st district heating company Reykjavik District Heating is now part of Reykjavik Energy

1944

- Experiment in geo-steam electricity at Reykjakot farm

1946

- Electricity Act provides for the establishment of the State Electricity Authority to advance knowledge on geo resource and utilization

1956

- Geothermal Department established in the State Electricity Authority
- Government launches rural electricity program that is completed in the late 1970s

1957

- Reykjavík and the State buy a oil drill rig with a capacity to drill 3,000 m deep wells.

1965

- Energy company Landsvirkjun is formed.

1967

- Energy Act of 1967 (in conjunction with the Water Act of 1923) indicates that the ownership of energy resource lies with ownership of the land, subject to restrictions (Energy Act 58/1967)
- State Electricity Authority becomes the NEA (Orkustofnun) and State Electricity Power Works splits as a separate organization

1969

- First program for exploration of the high temperature fields
- Bjarnarflag Geothermal Plant, located near Námafjall and Lake Myvatn in northeast Iceland, is the 1st commercial geothermal power plant to go on-line in Iceland

1969/1970

- Iceland's 1st aluminum smelter ISAI is built outside of Hafnarfjordur for a Swiss Aluminum company, now owned by Rio Tinto Alcan; and fueled by hydropower;

1973-1974

- Oil Embargo/first oil shock

1974

- Inflation 43%
- Hitaveita Sudurnesja was formed

1977

- Krafla's power production begins
- Svartsengi begins operations

Late 1970s

- Power line interconnection installed

1979

- Second oil shock, Iranian Revolution
- UN University established in Iceland for post-graduate training in geothermal energy
- Ferrosilicon smelter plant owned by Elkem opens at Grundartangi

Early 1980s

- Fishing quotas imposed

1980

- Legislation passed granting Hitaveita Suðurnesja permission to increase the electrical capacity by 6MW

1981

- Icelandic International Development Agency is established as an autonomous agency under the Ministry of Foreign Affairs
- Power Plant Act No. 60/1981

1983

- Akureyri acquires a share in Landsvirkjun

Mid 1980s

- Major increase in the number of fish farms

1984

- All major power stations were connected to the grid; all regions had access to hydropower, diesel-based power largely became used for reserves;
- Althingi modifies HS charter to heating/water and power (No. 91/1984)

1985

- 85% of the population uses geothermal heating.
- Althingi lowers state ownership of HS from 40 to 20% (No. 101, 1985);

1986

- Chernobyl nuclear accident

1990s

- Cod Wars

1990

- Ministry of Environment established

1993

- Iceland joins to the EEA, effective 1994

1995-1996

- New heavy industry contracts are signed
- Safety of Electricity Installations, Consumer Apparatus and Electrical Materials, Act No 146/1996

1997

- Planning and Building Act No. 73/1997

1998

- Resources Act 57/1998, supersedes the Energy Act 58/1967 and the Act on Ownership and Rights of Usage of Geothermal Resources No. 98/1940, and the Power Plant Act No. 60/1981
- Common Land and Boundaries of Private Land, Common Land and Highland Pasture Act, No 58/1998

1999

- Reykjavik District Heating is merged with Reykjavik Electricity and Reykjavik Waterworks to form a new company Reykjavik Energy (Orkuveita Reyjavikur)
- Hygienic and Pollution Act, No. 7/1998
- Monitoring Act 27/1999
- Nature Protection Act No 44/1999

1999-2003

- Master Plan, Phase 1

2000

- EIA Act, Act 106/2000 to avoid or minimize environmental impacts of projects; geothermal and other thermal plants of 50 MW and more are subject to EIAs

2002

- Karahnjukavirkjun hydropower project (690 MW) presented for a vote in Parliament

2003

- Natl Energy Authority Act, No. 87/2003;
- Electricity Act, Act 65/2003

2004-2010
- Master Plan Phase 2

2005
- Competition Act No 44/2005
- Major Protests occur over Karahnjukar Hydro project

2006
- Strategic Environmental Assessment Act, No 105/2006

2007
- Emission of GHG Act, No. 65/2007
- Government releases its Climate Change Strategy (#3)
- HS Orka is privatized .

2008
- Amendment to the Resources Act, No 58/2008
- Banking Crisis

2009
- A Steering Committee is appointed to advise on comprehensive energy policy for Iceland

2012
- Kyoto exemption expires
- The UK and Iceland sign a deal for a subsea cable.

Appendix Table A1: Icelandic Governments

Current Parties: Social Democrats/SD (Left), Left-Green/LG (Left), Progressives/P (Center Left), Independence/I (Center Right), Movement/M (Right)

Previous Parties: Citizens Party/CP, Liberals and Leftists/LL, People's Alliance/PA,

Party	Coalition	Prime Minister	Entered Office
Independence	I-SD	• Olafur Thors • Bjarni Benediktsson (acting) • Olafur Thors • Bjarni Benediktsson • Johann Hafstein	1959 1961 1962 1963 1970
Progressive	P-PA-LL	• Olafur Johannesson	1971
Independence	I-P	• Geir Hallgrimsson	1974
Progressive	P-PA	• Olafur Johannesson	1978
Social Democrats	SD	• Benedikt Grondal	1979
Independence	I-P-PA	• Gunnar Thoroddsen	1980
Progressive	P-I	• Steingrimur Hermannsson	1983
Independence	I-P-SD	• Thorsteinn Palsson	1987
Progressive	P-SD-PA P-SD-PA-CP	• Steingrimur Hermannsson	1988 1989
Independence	I-SD I-P I-P I-P	• David Oddsson	1991 1995 1999 2003
Progressive	P-I	• Halldor Asgrimsson	2004
Independence	I-P I-SD	• Geir Haarde	2006 2007
Social Democrats	SD-LG SD-LG	• Johanna Sigurdardottir	2009 2009

Source: Halfdanarson, 2008; Creative Commons, accessed 8/16/12.

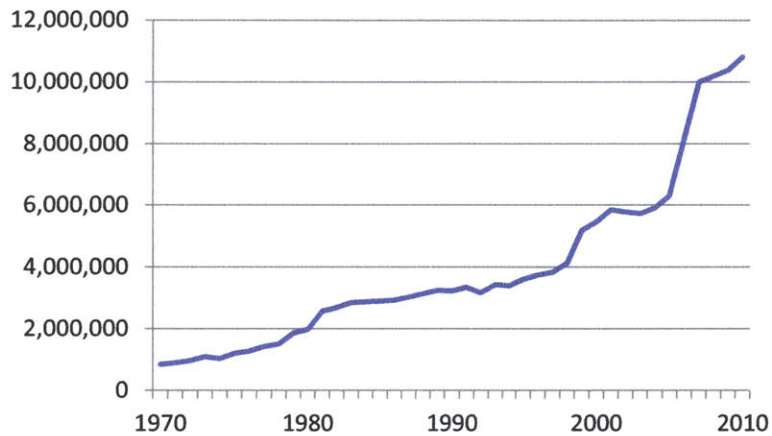
Key Recent Policies

- Act on Electric Generating Stations, No 60/1981
- Act on Landsvirkjun, No 42/1983 (amendments through 2011)
- Act on the utilization of ground resources, No 57/1998
- Act on the creation of the Hitaveita Sudurnesja, No 106/2000
- Act on the evaluation of environmental impact, No. 106/2000
- Electricity Act, No 65/2003 (based on EU Dir No 96/92)
- Act on the establishment of Landsnet hf., No 75/2004
- Act on the guarantee of origin of electricity produced from renewable energy sources, etc No.30/2008
- Act on water, No. 20/2006
- Act amending various acts on the law related to natural resources and energy, No. 58/2008
- Various regulations on the provision and distribution of heating services for a number of individual communities/municipalities

Carbon Change

Savings from avoided carbon with the adoption of geothermal energy were calculated with the same coefficient method applied in the other cases. Geothermal energy is assumed to displace oil, given trends shown above. This method for simplicity assumes a 1:1 replacement.[25] For the period studied, 161.8 million t CO_2 were cumulatively avoided in the total primary energy supply from 1970 to 2010 by using geothermal energy in lieu of oil (Figure A1). This amounts to roughly 4 million tons on average per year.

Figure A1: Avoided CO_2 *(t CO_2)*



Source: Data for geothermal energy in the total primary energy supply is from IEA, 2012. Avoided CO_2 assumes geothermal energy replaces oil on a direct content basis, applying a co-efficient of 74.1 t CO2 per TJ for substituted oil (Herold, 2003).

This does not account for CO_2 emitted throughout the lifecycle of the process, such as with the emissions produced in drilling/exploration and plant construction, or the more limited amounts emitted from utilization of the geothermal fields.[26] For those considering

[25] Recent country level reporting on carbon emissions by Italy and Iceland have not included those associated with geothermal generation, as it is considered to be a form of natural flux. In line with this, carbon releases from the geothermal plants are excluded from the above calculations.

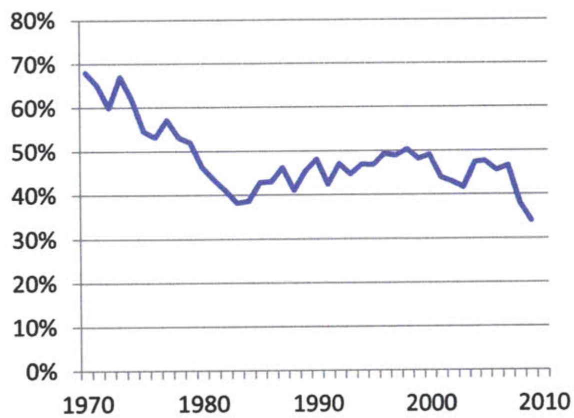
[26] With respect to the geothermal field usage, research is being done on carbon mineralization (Olafsson, Undated).

this case more broadly, the calculation does not account for the CO_2 emitted by the heavy industries which use geothermal based electricity.

Import Dependence

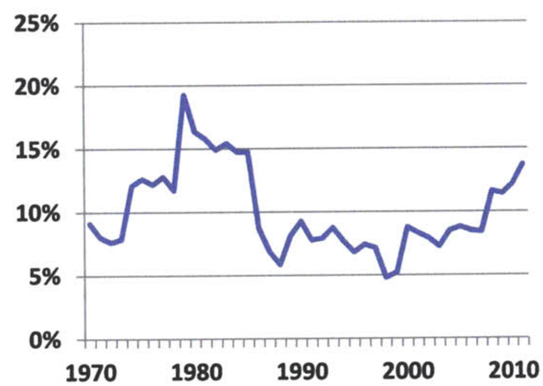
Specific to energy self-sufficiency, Iceland shows a significant improvement with net energy imports as a share of total energy consumed between 1970 and 2010, decreasing from nearly 70% to a little more than 30% (Figure A2).

Figure A2: Net Energy Imports as a % of Final Energy Consumed



Source: IEA data, 2012.

Figure A3 Petroleum and Petroleum Products as % Imports
(Trade Balance)

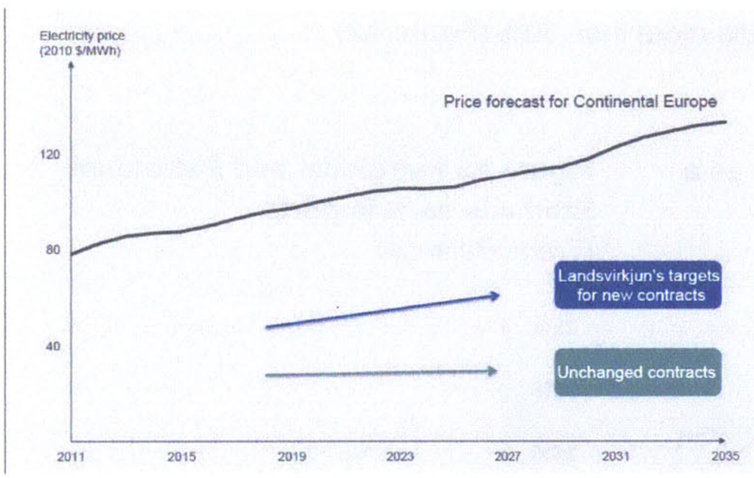


Source: UN Comtrade, SITC Rev 1 data, 2012.

Turning to the import effects of petroleum for total trade, Figure A3 shows a doubling during the oil shock period which subsequently diminished. Notably, petroleum imports as a percentage of total imports (current $) have risen from <10% to almost 15%, if the end points of the transition are considered. This indicator obviously has limitations, since it is influenced by conditions which include not only oil price flux, but currency valuations changes, and variations in import preferences.

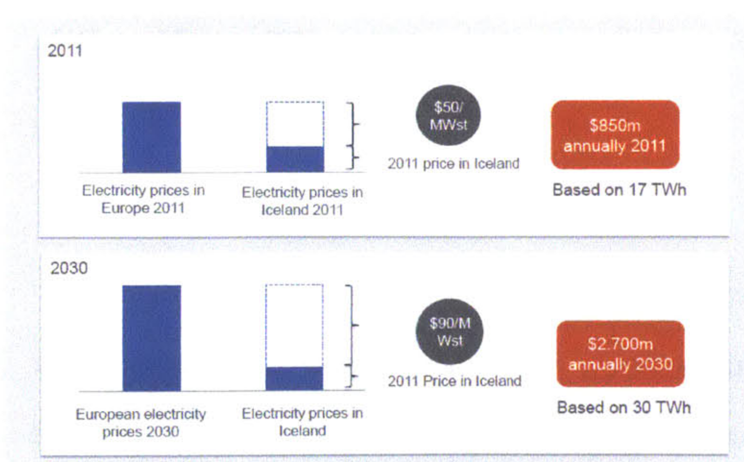
Additional Charts and Tables

Figure A4: Electricity Pricing, View #1, as noted by Landsvirkjun



Source: Landsvirkjun, 2011.

Figure A5: Electricity Pricing, View #2, as noted by Landsvirkjun



Source: Landsvirkjun, 2011.

Table A2: Landsvirkjun's Largest Customers

Client	**GW**	**Price base**
Alcoa	5.040	Aluminum linkage
Rio Tinto Alcan	2.930	US CPI (from Oct 2010)
Nordural	1,570	Aluminum linkage
Jarnblendifelagid	1.055	Norwegian CPI
Becromal	565	Gradual price increases in $

Source: Reitun, 2010.

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Chapter 8

Conceptual Models and Analysis

This chapter provides a synthesized overview of research findings. It begins by presenting three conceptual models to explain national energy system transitions. It then applies the models to transition performance indicators, highlighting a number of observed patterns. Discussion turns then to key innovations, drivers and barriers, and pre-conditions, briefly examining an underlying question which asks whether the presence of natural resource endowments largely or deterministically explains the occurrence of the low carbon transitions of this study. The chapter concludes by considering implications for theory and practice.

In short, central findings indicated that significant change in national energy systems occurred in less than 15 years; that technology complexity was not always a major impediment to change; and that countries of different governance approaches and consumption levels effectuated significant energy change. Additionally, low carbon energy technologies were adopted before they were competitive, yet the majority became competitive in the adoption process. These developments were attained as countries also improved their overall quality of living. Among key pre-conditions, three emerged as significant: the role of readiness; the instrumentality of public actors; and the aptness of policy.

A. CONCEPTUAL MODELS of NATIONAL ENERGY TRANSFORMATION

How, in fact, did the four countries in this study effectuate change to specific forms of low carbon energy? The energy transitions in this study involved a rich set of dynamic interactions. To comparatively explain and analyze these shifts, conceptual models can provide a way for identifying and efficiently evaluating the research. Three, basic conceptual prototypes are put forward, here, based on predictive and explanatory attributes that were observed. Each model reflects a type of country-level readiness, based on infrastructure, markets and industry, technology expertise, and existing utilization of the energy at the initial point of the period that is evaluated. These models are as follows.

- ***Ramp:*** A country displaces traditional fuels by scaling up a preferred type of energy that is already fairly established in domestic use. This leveraging of an existent and continuous energy pathway principally entails building out of markets, technologies, and industries with capabilities from established institutions and expertise. Some adjustments may occur with infrastructure or technology, for example. However, significant new expertise is largely unnecessary.

- ***Reconstitute:*** A country re-purposes a technology, industries and/or markets in order to scale up energy that is not in use or is of limited use. This reconfiguration typically entails significant re-development in infrastructure, institutions and practices, as well as widespread supplier and user learning, diversification of existing industries, and possibly creation of new types of market players.

- ***Establish:*** A country introduces technology, industries and markets for a type of energy that is essentially not in domestic use at the time in order to scale the preferred energy type. This discontinuous approach may create or borrow new technology and markets, producing a new industry. It is characterized by the development of new expertise and forms of infrastructure; substantial uncertainty; emergence of new kinds of market players; and major path dependence challenges.

By design, these conceptual models are simple to allow for explanatory breadth, but can be elaborated with more sophisticated nuances. A variant, for example, which accounts for a disrupted energy trajectory (i.e. an early adoption disappears to then later reemerge with recreated technology) might be distinguished as a hybrid between the Establish-Reconstitute models. In some instances, components of various models may also be evident within a tested case, especially if the case is evaluated over a lengthy period. Judgments of fit must be then made based on what are deemed to be dominant aspects of a model and case.

Among the cases that were studied, the conceptual models were seen as follows: France and Iceland reflected Ramped change; Brazil represented Reconstituted change; and Denmark was an example of the Establish model of change.

Ramp model: French nuclear energy

The French nuclear energy transition, triggered by the Messmer Plan in 1974, leveraged an already existent energy transition together with incumbent institutions and expertise. The French government accelerated nuclear energy adoption within the existing power market through the mobilization of key state actors and the expansion of the nuclear fleet. Some adjustments occurred with the fuel supply and reactor manufacture, building heavily upon institutional and knowledge capabilities in place for the civilian and military-based nuclear programs.[1]

Ramp model: Icelandic geothermal energy

The Icelandic geothermal energy transition robustly scaled from an energy transition that was well underway since the early 20th century. While sub-trajectories for geothermal heating and geothermal power evolved differently, the overarching energy path built primarily upon existing markets, technologies and industries. Market players and infrastructure were added by municipal energy companies and the National Power Company leveraging indigenous capabilities and expertise, such as that of the National Energy Authority.

[1] Traces of the Establish and Reconstitute models can be found in this case with, for example, the early use of the Westinghouse license and modification of the fuel cycle. However, neither appeared to define the overall transition. Nuclear power was already established and in continuous use in the power sector. Many key experts and institutions were also already in place.

Reconstitute model: Brazilian biofuels

The Brazilian biofuels transition was launched in 1975, as part of the government's ProAlcool Program. The Program, in essence, reconfigured three existing markets: sugar, automobiles and gasoline to constitute an ethanol market and industry (with biodiesel appearing much later). This transformation involved changes in infrastructure and practices associated with agriculture and sugar distilleries, automobile production, and fuel distribution with significant learning related to automotive technology, horticulture and farming.

Establish model: Danish wind power

In Denmark, the wind energy transition was initiated from a nearly non-existent wind energy path at the time with early actions of entrepreneurs, scientists, and other members of civil society developing novel wind turbine technology and adapting the discontinued Gedser design from an earlier era. A new industry emerged quickly in the late 1970s and early 1980s, and domestic market for wind power was created. The industry experienced early challenges with bankruptcies and grid integration, undergoing successive growth spurts associated with changes in international as well as domestic markets. New kinds of actors emerged, including wind power cooperatives, associations for wind turbine owners and manufacturers, and balance-responsible market players. Wind power substitution occurred principally in the past two decades.[2]

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[2] Elements of the Reconstitute model can be found with companies, like Danish agricultural machinery producer Vestas, and historical ship-building skills shifting from traditional focus to wind turbine manufacturing. However, markets did not appear to have been substantially repurposed and there was no notable

B. TYPOLOGIES, TOOLS and ROBUSTNESS of CHANGE

In Chapter 2, general propositions were formulated to characterize energy transitions, based largely by the degree of governmental intervention and mode of change. In light of findings from the testing of the proposed typology, a classification scheme is proposed here in more sharpened form to account for nuanced dimensionality relating to conduits of change and whether participation is optional.[3] This by no means exhausts

[3] Provisional categories of transitions in Chapter 2 included emergent, induced, hybrid, and deployed transitions. Induced change referred to a transition in which a national government would take the leadership. This category is now sub-divided into mandated and encouraged inducements. Mandated refers to transitions accomplished primarily through statutory requirements in which the actual conversion is executed by non-state actors. An example is a mandate for ethanol blending to be carried out by independent fuel distributors. By contrast, change that is encouraged, but not mandated, can be achieved using measures like incentives, information or suasion. These latter inducements generally leave the details of implementation to non-state actors. These sorts of caveats resonate with today's discourse on national energy policy, where concerns may exist with government defining all the details of an energy transition it wants to attain. There is an observable preference on the part society for greater societal volition.

Another significant dimension that merits amplification is 'deployed' change. The original description presumed that the government would be in charge. However, state-owned or partly state-owned actors and the use of government contracts implemented by third parties are important variants to this construct. For the purposes of this research, all of these variants fall into the deployed category; nonetheless, the nuances are worth highlighting.

The definition of government can also be differentiated in terms of tiers of oversight. Energy system change can, as noted earlier, occur at the local, regional/state, national or supra-national levels. Municipalities, for example, were an important locus for the energy transition in Iceland, where local authorities often sought geothermal-based district heating. Within a national energy transition, then, multiple layers of government can factor importantly. This research maintains its national government-centered focus, as it is designed fundamentally to inform national decision-making; nevertheless, the importance of thinking about implementation in a pluralistic context is recognized.

The hybrid transition category raises still another point which merits elaboration. Different kinds of hybrid combinations have distinct political and financial meaning. For example, a 'pure mix' of government, industry, and civil society inputs in a transition the range of dimensions which could be included. Figure B1 illustrates refinements with the transitions of this study indicated. Essentially, the Danish and late-staged Brazilian transitions both involved notable, bottom-up led transformations, whereas the French transition and early-staged change in Brazil were more top-down processes. Iceland's transition was the closest to a genuine hybrid transition.

Figure B1: Source and Modality of Energy System Transitions

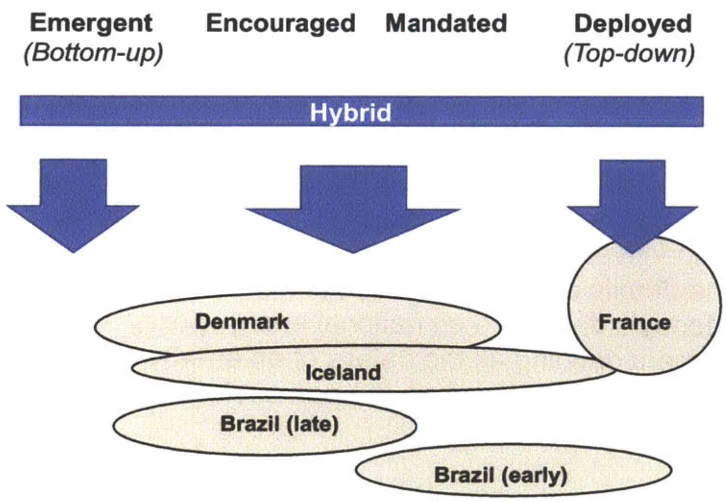

Table B1 breaks down and elaborates a number of the transition taxonomy dimensions. In addition to the locus and direction of the transition, three other dimensions include: (1) the robustness of traditional energy displacement; (2) key forms of governmental intervention; and (3) the type of technology and system shifts involved.

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differs markedly from a hybrid in which government drives the early stages of conversion and industry carries progress the rest of the way, as was the case in Brazil.

Table B1: Types of Energy System Transitions Based on Different Attributes

Country (Prototype)	**Source of Change**	**Robustness of Critical Energy Substitution**	**Major Forms of Governmental Intervention**	**Key Change at the Technical and System Levels**[4]
France (Ramp)	Top-down (Messmer Plan)	*Nuclear power % electricity:* Robust, front-end scale-up; in 10 years from 1975-1985 (10-65%) or in 15 years between 1975 and 1990 (10-75%)	Deployment: Implemented by state actors;	Technology: Radical change in some PWRs for load-following and MOX, 3 to 4 loop design, size; Incremental change in safety and other functions; System: Radical conversion to 58 PWRs in ˜25 years, also with development of the industrial fuel cycle and load-following practices;
Iceland (Ramp)	Hybrid (space heating) Bottom-up (CHP) Top-down led (power for heavy industry)	*Geothermal energy % heating:* Robust, front-end (space heating) 43 to 83% population in <15 years (1973–1984) *Geothermal energy % electricity:* Limited change with CHP; Robust, back-end change with power for heavy industry in < 15 years, 1997-2010	Deployment: Implemented primarily by state and municipality actors; Encouragement: Deals for heavy industry; Information: Resource assessments;	Technology: Incremental and radical change with exploration and drilling, site- specific process engineering and plant (re)design System: Radical change evident with industry spillovers in fish farming, de-icing, tourism, etc

[4] Note: Criteria for distinguishing radical/disruptive from incremental development can be based on the extent of observed change in physical aspects or direct use, or be based on observed process outcomes. A composite is used here.

		(7 to 26%)		
Brazil (Reconstitute)	Top-down led (early, ProAlcool); Bottom-up led (late, ethanol/ flex fuel); Top-down led (late, biodiesel)	*Ethanol % auto fuels:* Robust, front-end substitution in 10 years from 1975-1985 (1 to 41%), reaching a high in 1988 < 15 years (51%); Later, more moderate, new scaling was evident in < 10 years (31 to 41%) following a period of retrenchment	Deployment: Implemented in part by state actors Petrobras, BNDES, deal w/ auto-manufacturers, etc; Mandates: blending requirements; Encouragement: Soft financing; Information: Resource map with new zoning;	Technology: Radical change with neat and flex fuel technology, new seed varieties; incremental and radical changes in agricultural practices System: Radical change with fleet conversions, agricultural yields
Denmark (Establish)	Bottom-up led combined w/ some top-down steering	*Wind power % electricity:* Slow and negligible front-end change, followed by robust, back-end scaling (2 to 28%) in 15 years, 1996-2011;	Deployment: Government-utility deals; Mandates: Equipment standards and grid connection requirements; Encouragement: Tax credits; Information: Resource maps	Technology: Mostly incremental advances with wind turbines and wind analysis tools over time; System: Radical change included offshore wind technology and the power system shift to distributed generation;

When viewed together, Figure B1 and Table B1, emphasize how the French case was the epitome of a top-down energy transition with system change effectuated by the national government. This enabled a very rapid scale-up of nuclear power with marked substitution of fuel, advancing from 10 to 65% of total electricity in just ten years between 1975 and 1985. The French national government relied principally on direct deployment of the Messmer Plan by its public agents as its form of intervention. Radical change was attained at the technology and system levels with adaptations in some design, functionality, and use of 58 pressurized water reactors.

Somewhat differently, Brazil embodied a very clear 'bifurcated hybrid' transition in which the initial phase was top-down led by a military regime government and the latter stage (ethanol) was bottom-up led by industry. Early scaling of ethanol as a share of automotive fuels evidenced a striking increase from 1 to 41% in 10 years. Recent scaling occurred with a more moderate, second staged increase from 31 to 41% in less than 10 years. Governmental intervention centered on very rapid market realignments in the early years. A portion of outright deployment was carried out by state actors, like the state-owned energy company Petrobras, and facilitated by the national development bank BNDES. Important policy tools included the use of fuel blend mandates, soft financing, and resource maps. Overall, radical change was in evidence at the technical level with vehicle design advances and new seed varieties. At the system level, radical change was seen in the conversion of the automobile fleet and agricultural yields.

Iceland exemplified a more blended, hybridized transition. The shift to geothermal-based electricity associated with combined heat and power was bottom-up led and incremental. The transition in electricity that powered heavy industry was top-down led and accomplished through intensive promotion by the government and National Power Company's marketing office combined with incentive packages. This change occurred in recent years, altering the share of electricity from geothermal energy from 7 to 26% in less than 15 years. With space-heating, where a robust front-end energy conversion occurred, the source of change is quite mixed as some substitution originated with localities seeking/implementing district heating conversions, while other shifts were defined by state actors guiding localities or implementing the change. Robust substitution occurred between 1973 and 1984, shifting the geothermal heating coverage of the population from 43 to 83%. Overall, incremental as well as radical change was evident at the technology level with exploration and drilling, process engineering, and plant design. Considered at the system level, radical change was evident with spillovers into fish farming, de-icing, and health and tourism.

Finally in Denmark, a bottom-up led hybrid transition was initiated by actions of entrepreneurs, local community owners, NGOs, scientists, etc. This was quickly complemented by government steering with regulations (i.e. standards and grid connection requirements), incentives (i.e. tax credits and a market premium[5]) together

[5] One could classify a market premium as a regulation, rather than an incentive, since a price is stipulated for generation that is provided. For the purposes here, the policy tool is treated as an incentive, since the covered action (provision of generation) is optional. As with other clarifications, the scope and orientation of framing can bound the action being described.

with some outright deployment in the form of government-utility contracts. In short, a domestic industry and market were formed with notable back-end scaling of wind-based electricity from 2 to 28% in the 15 years between 1996 and 2011. For this case, incremental change was largely evident with wind turbine and analysis tool advances at the technology level, while radical overall change was evident with offshore wind technology and the power system shift to more distributed generation.

In sum, the three conceptual models provide a framework for explaining national energy transformations and analyzing different approaches. The Ramp model reflects situations in which a country is primed and ready for scaling, while the Reconstitute and Establish models represent situations requiring more substantial retooling, and fundamental, learning occurs. For the transition typology, the top-down approach relies significantly on state actors and more centralized planning, whereas, bottom-up efforts tie to actors outside of the state's sphere.

Specific to the degrees of change for sectoral or fuel class substitution, at the lower bound were case shifts of at least 10 percentage points and, at the upper bound, shifts evidenced change of up to 55 points. The important link between the extent of energy substitution and country-level readiness is discussed more fully in the following section.

With respect to policy tools, instruments varied between the more emergent markets (Reconstitute and Establish models) and the more primed markets (Ramp models). The Reconstitute and Establish models focused heavily on market formation with standard setting, procurement policies, financing, zoning and knowledge expansion. Policy measures in more primed settings relied more on outright deployment by public actors. Policies are explored further later in this chapter.

C. ANALYSIS of CHANGE INDICATORS and NEAR-TERM DURABILITY

System change indicators were comparatively evaluated for the following:

- the Extent of change in the relative and absolute amount of the low carbon energy (substitution and diffusion)
- Cost improvements and competitiveness
- Societal acceptance
- Industrial development.

Among more significant findings was the insight that the more significant substitution occurred in the Ramp and Reconstitute models. Cost improvements were also evident in all cases. In terms of early cost competitiveness in the 1970s, only geothermal-based heating reflected this preliminary condition, but by the end of the studied period Brazilian ethanol, Icelandic geothermal-based electricity and French nuclear-based electricity were also cost competitive. Notably, the transitions in all cases occurred while each country improved its quality of living, as gauged by the Human Development Index to also be discussed.

Energy balance

Changes in energy mixes are fundamental to understanding the extent of a transition over time. Table C1 summarizes energy data in absolute unit and relative terms at the national and sectoral or fuel supply levels. Figures C1 and C2 illustrate thematic trends with Table C1 data. Focusing first on energy substitution, Figure C1 shows a basic, linear pattern of substitution progressing from the largest displacement to smallest in direct relation to the sequencing of models from the Ramp to Reconstitute and finally the Establish form of change. The most extensive displacement of total primary energy by a specific form of studied low carbon energy can be seen in the more mature, Ramp models associated with France and Iceland. Interestingly, these two countries are the largest and smallest energy consumers among countries of this study (2010), so the scale of energy consumption does not appear to be an important explanatory factor.

Figure C1: Conceptual Models and Energy Substitution
(Readiness vs. Relative Change in Total Primary Energy)

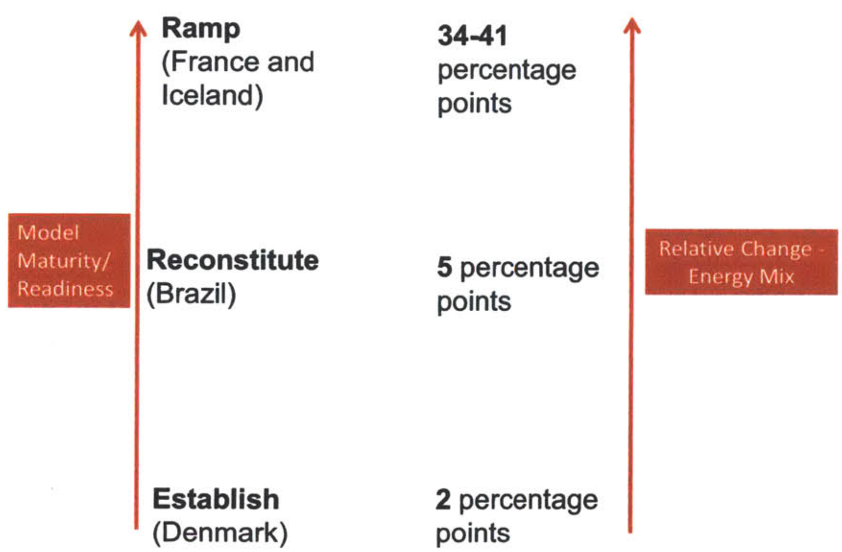


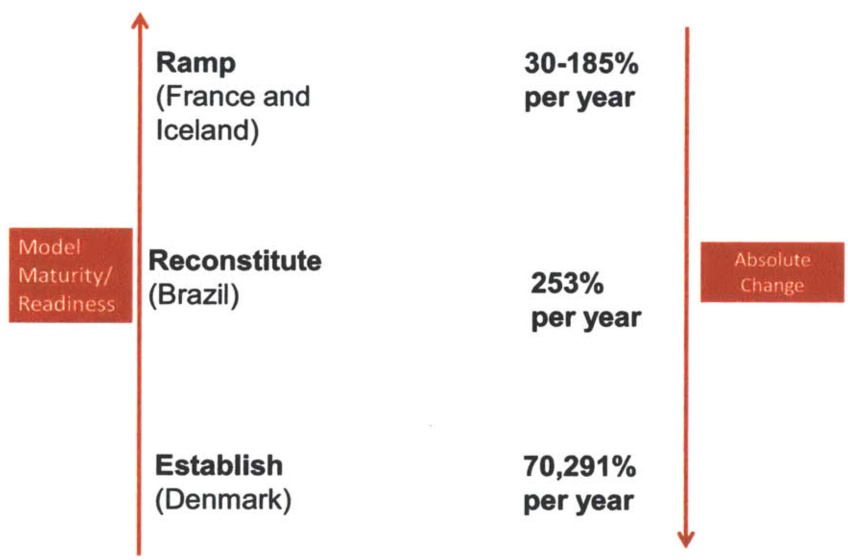
Table C1: Summary of Energy Balance Change

Energy *1970-2010, unless noted*	**France**	**Iceland**	**Brazil**	**Denmark**
	Ramp model	*Ramp model*	*Reconstitute model*	*Establish model*
Studied energy & total primary energy$_{2010}$	4,676,314 and 11,062,792 TJ	145,839 and 224,262 TJ	550,825 and 10,055,086 TJ $_{2009}$	28,117 and 824,082 TJ
Change in shares of studied energy in total primary energy (TPES)	<1% to 42%	31% to 65%	** <1%$_{1971}$ to 5%$_{2009}$	<1% to 3%
Change in shares of studied energy in key sectors/fuel classes	Electricity 4% to 76% or ~2% per year	Electricity 1% to 26% or <1% per year Space heating 43% to 90% population or ~1%/year	Automotive Fuels 1% to 41% or ~1% per year	Electricity 0 to 20% or <1% per year
Change in studied energy produced per year (TPES)	185% per year	30% per year	253% per year 1971-2009	70,291%** per year

*Sources: Chapters 4-7. Notes: *Biofuels includes biogasoline, biodiesels and other liquid biofuels. **The base year is set to 1 for comparable calculations. The actual amount equals 0.*

Turning to the levels of absolute growth (diffusion), the conceptual models again reveal a basic, linear progression, but the converse of that seen with substitution. Figure C2 shows Denmark's Establish model of a newly developed industry and (re)created technology exhibiting the highest degree of absolute growth. Brazil represented an intermediate level of absolute growth while the two ramped examples reflect the least amount of absolute growth. This can easily be understood by the fact that less mature/primed models begin from a much smaller base, so initial scaling will in percentage terms be more pronounced.

Figure C2: Framework Models and Energy Diffusion
(Readiness vs. Absolute Growth)



These observed trends for maturity or country-level preparedness hold some predictive capacity in relation to diffusion and substitution, yet limits can be expected. Mature markets, for example, can reach saturation points and taper off, in which case preparedness for scaling may exist in latent form, but not be effectuated (see S curve discussion, Chapter 3).

At this juncture, it is useful to highlight a number of additional distinctions related to governmental intervention and energy substitution. The two countries demonstrating the greatest level of energy displacement, France and Iceland (Ramp models), implemented targeted strategies centered on oil substitution (at least in the early stage) that were largely carried out by public actors. These same countries also relied on more centralized applications of energy technology that were in more advanced stages of development relative to the other cases.[6] Like France and Iceland, Brazil (Reconstitute model) employed a robust and targeted early strategy implemented partly by public actors, but there is an important decentralized quality to its automobile-biofuels technology. Denmark's approach to energy system change (Establish model) for the period of this study was characterized by highly diversified, parallel and robust developments pursued along multiple energy technology lines.[7] Perhaps more compelling for the Danish case is wind power's intermittent character. Absent good storage, it has a natural penetration limit that is not as obvious with the other technologies that were studied. The Danish power system also became more decentralized as a result of the integration of distributed wind turbines and district heating. In sum, top-down and targeted energy strategies may be more effective with centralized applications of energy technology in conditions warranting urgent action.

[6] Distinctions in the maturity of technology and market merit further study.

[7] Brazil also supported development of diverse fuels with varying degrees of focus over time.

Costs

Costs present an interesting, quantitative way to gauge the extent and durability of an energy system transition. The links between accumulated production and cost reduction are widely recognized for their connection to learning (Wilson, forthcoming). However, cost reductions are not guaranteed with greater production, since uncertainties and other contextual determinants, like factors at the firm and industry level, play a role (Ibid, citing Weiss et al, 2010; Grubler, 2010).

In this study's examination of costs, some (but not all) data was uniform. It is also important to underscore that cost performance comparisons are necessarily focused, here, as different technologies are evaluated from non-comparable domestic markets. Recognizing such complexities of analysis, this study evaluated whether cost improvement and cost competitiveness were evident in each of the cases. This is based in part on the assumption that improvements in the price of new or emerging technologies are often closely associated with increasing returns of diffusion (Arthur, 1989; Bergek, 2002). New technologies are typically at a comparative disadvantage relative to price as compared to incumbent technologies (Bergek, 2002).

Case assessments (Chapters 4-7) and Table C2 revealed cost improvements all cases, but France, with some caveats. Notable improvements were evident in the overall production costs of studied technology in Brazil and Denmark (Chapters 4 and 5). For France (and other nuclear states in North America and Western Europe), project costs and construction times have risen for nuclear energy installations (Chapter 6). With

Icelandic geothermal energy, heating costs increased slightly, but appear to be mostly flat (Chapter 7). Data on the cost of production of geothermal heating and power generation were limited, but improvements were found in electricity. In available data across the cases, one finds that increased diffusion is associated broadly with cost improvements.

Cost competitiveness was also considered for transition performance and durability with the understanding that novel technologies may be costly (Rosenberg, 1994). Substantial cost declines are expected to occur only after a significant amount of commercial trial and error in tandem with industrial development, standardization and mass production (Grubler 1998).

Among the cases studied, none, with the exception of Icelandic geothermal energy in space heating, appears to have been competitive at the beginning of the 1970s. Since then, Brazilian ethanol has become competitive relative to international gasoline prices (while more recently emergent biodiesel vis-a-vis diesel prices is not competitive). For Danish wind, costs are not yet fully competitive, although by some accounts, Danish wind power costs are competitive with new CHP (DWIA, 2012). In any event, Danish wind power costs have markedly improved and are approaching more widespread competitiveness in areas with strong wind resources. For French nuclear power, costs associated with production from existing plants are competitive; however, new project costs which may alter this. Icelandic geothermal energy costs are competitive for heating and now for power. This indicates that energy transitions can occur with less conventional energy technologies that are not yet cost competitive, but can lead to cost improvements and cost competitiveness in the process. Such change can also occur in conjunction with other co-benefits. [8] Notably, each of the four countries in this study showed clear improvement in the trending of its human development – a composite indicator which integrates health, education, and living standard (United Nations Development Program/UNDP, 2012; see Appendix).

Societal acceptance

Societal acceptance serves as a more qualitative gauge of the extent and durability of energy system change. If a transition is not desired or ultimately accepted by a society, this condition may ultimately undermine it. The four cases offered incomplete, albeit interesting insights on this. Broad acceptance was evident in Brazil, Denmark and Iceland, particularly over time. In Brazil, societal acceptance of ethanol appears to be widespread. The reaction to biodiesel is mixed, as this fuel is not competitive in terms of cost or productivity. Yet when policy support for it is considered in the context of regional development and jobs, the effort appears to be more widely accepted. Wind power in Denmark also appears to be broadly accepted, with some niches of occasional opposition. In Iceland, geothermal energy similarly appears to be widely accepted, although localized concerns about emissions and seismicity exist. Where societal acceptance is less certain in Iceland relates to the promotion of energy-intensive industries which can translate to increased use of geothermal energy. In France,

[8] Note: for technologies to grow through investment, a good and stable rate of return is needed, which can stem from cost competitiveness, public policy support, or public investment and no risk.

nuclear energy continues to be contested. Absent a full-scale referendum and deeper study focused singularly on this, a more complete 'read' of acceptance is at best speculative.

In sum, the trends in societal acceptance do not illustrate any predictable associations in relation to the conceptual models, underscoring the subjectivity of societal acceptance. However, one important insight is that a robust energy system transition can occur even in the face of a divided society.

Industrial development

Industrial development provides a more blended, quantitative-qualitative gauge of energy transition performance and durability. It is generally accepted that scaling up of an energy technology can contribute to domestic industrial development if relevant products and/or services are provided domestically. In the transitions studied here, economic growth was clearly a by-product of technology innovation and adaptation. These countries also emerged as international leaders in their respective energy technologies. Denmark's wind manufacturer Vestas is ranked first worldwide in the wind power industry. France's Areva and EDF are positioned among the top globally for their respective products and services. Brazil ranks second for ethanol production, with its 400+ ethanol market players, and leads in flex fuel vehicle use with a specialized automobile sector. Iceland's industrial standing is not well documented as international indices on geothermal industries appear to be less readily available. Nonetheless, other signs point to Iceland's prominent standing in geothermal energy. Iceland is partnering with the World Bank to consult on geothermal projects in African countries and has been a leader in post-graduate geothermal training internationally through its UN University Geothermal Programme for more than three decades.

When viewing the indicators of change holistically, a number of highlights were evident. Substantial energy conversions occurred in markets that were more primed for change (Ramp model), scaling quickly and early. Significant diffusion, as gauged by absolute growth, occurred in markets that required more retooling or outright development. Cost competitiveness was more readily apparent in models which evidenced greater maturity/readiness. With respect to industrial development, trends of progress were evident, although not vis-a-vis the conceptual models.

Table C2: Summary of Transition Viability Measures

Measures	Brazil	Denmark	France	Iceland
Costs *Improvement*	Improved production costs and yields	Substantially improved production costs over 4 decades with some recent increases in costs/MW worldwide	France has some of the least cost electricity in Europe, yet new project costs and construction times have increased in France and other regions	Limited data available on electricity and heating production costs; prices for heating have remained mostly flat;
Competitive	Brazilian ethanol is competitive and compares well vs. market-priced gasoline and across other countries' ethanol costs	Danish wind power not yet widely competitive, but compares well vs. other country investment costs	French nuclear energy is competitive; Regionally low prices w/ plant life extension and depreciation.	Icelandic geothermal energy is competitive; Development costs are low vs. some geothermal countries.
Societal Acceptance	Broad-based for ethanol; some questions related to biodiesel	Broad-based with some opposition over time; new shift toward greater wind power and other renewables	Varied	Broad-based

Industrial Development	Growth and enhancement are evident, although challenged by current domestic market dynamics	Growth and enhancement are observed with new domestic opportunities emerging; mixed international opportunities	Growth and enhancement are evident; opportunities possible for increased nuclear-based electricity, power plant and services exports; greater uncertainty in recent years for the domestic and international market	Growth and enhancement are evident with notable industrial spillovers and improved overall efficiencies; opportunities for spillovers, new industry, and exports; domestic heat and power market appears mostly saturated

The Near-term Durability of Transitions

Looking more broadly at the durability of transitions, all four transitions appear to be well-positioned to maintain their trajectories for the next 5-10 years. There are, however, "game-changers" on the horizon that could alter the paths.

Cellulosic ethanol and electric vehicles are both transport technologies that are technically viable and advancing, although they are not fully proven economically. If either of these technologies attains a competitive level of commercial viability, it could diminish the market share for sugarcane-based ethanol and other biofuels. Brazilian producers could then fall back on markets for sugar and bio-electricity. This capacity to shift fluidly between markets (and the institutional architecture which accompanies it) could allow the ethanol market to survive in a more varied and competitive landscape.

In France, the long-standing existence of public opposition to nuclear energy, the recognition of newer and a wider array of energy options, and advances in public participation mean that nuclear power is not discussed as the sole option in current energy discourse. When considered with the knowledge that the nuclear fleet is reaching obsolescence (even with approved upgrades) and a new generation of experts is also needed, it is quite possible that alternative energy paths, including greater diversification, may redefine the French energy mix over the next decades.

For the other two countries, the existing energy paths appear to be well positioned to sustain. In Iceland, geothermal energy is a proven, widely accepted and reasonably priced form of reliable energy. Potential obstacles may exist in issues of energy use by subsidiaries of foreign companies and in localized environmental considerations. With respect to the skewed energy profile, efforts to diversify the Icelandic economy with data centers and eco-tourism could conceivably modify the path in a way which maintains or encourages geothermal development. As with localized environmental concerns of the past, solutions will need to be engineered. For Denmark, the near-term appears very promising with a shift back to renewables and deeper commitment to pursuing a green energy trajectory. The widespread EU focus on renewables might also lead to improved grid capacities and an offshore regional wind platform. As neighboring countries adopt more wind power, Danish wind experts could be highly sought after, but Denmark will also need to be more strategic in how it deals with cross-border smoothing of variable power flux.

D. INNOVATIONS AND ADAPTATIONS

Current debates on national energy policies are often premised on the idea that innovations are needed and can be triggered. Discussion then invariably turns to deeply divergent philosophical views of how to stimulate (for some, accelerate) innovation. Should government be involved or can this adequately happen if left to the market?[9]

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[9] Proponents of governmental intervention often contend that such action is justified on the basis that: energy is critical to economic and human development; public goods aspects related to the environment, public health and security warrant intervention; and jurisdictional accountabilities associated with domestic natural resources by definition entail some governmental reach (IPCC, 2011; UNDP et al, 2000). More specific to innovation, proponents of intervention point out that gains, like those associated with low carbon energy, have high social returns. As a result, businesses are often less inclined to step in, unless gains can be certain and appropriated (Anex, 2000; Suurs and Heckert, 2008; Borup et al, 2008).

Opponents of government intervention argue that government should not be choosing winners and losers explicitly or implicitly by prioritizing efforts (Alabama Policy Institute, This research found that energy transitions could be catalyzed without initial innovation through outright deployment or well-conceived mixes of policy instruments. Critical innovations and adaptations then occurred at various junctures and in different sectors, in some instances when government was not directly leading the change. Nonetheless, public actors and policy played an important role in each of the transitions.

In Brazil, for example, industry and research centers were the hubs of innovation during times of heavy governmental involvement in the 1970s and 1980s, when the market was reconfigured, as well as in later years when government was largely absent (Chapter 4). Strong governmental involvement and favorable policies are readily apparent in the early commercialization of the neat vehicle and some seed and agriculture developments. However, the flex fuel breakthrough, later-staged seed and agricultural innovations, and mechanization were driven largely by other sectors, during a period when policy intervention was limited, if not contradictory.[10]

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undated). This rationale is predicated on the idea that the market inherently encourages efficiency as well as innovation.

In the above kind of debate, proponents of government intervention must account for public-based strategies that may be less efficient than industry-driven counterparts. Opponents must factor for the reality that markets are imperfect, and efficiencies as well as innovation may not happen as quickly or adequately as society deems necessary (Jaffe et al, 2005).

[10] Early gains in sugarcane yields are linked to R&D of the sugar industry cooperative Copersucar and its research center (CTC) together with governmentally-owned Planalsucar (Ibid). The neat vehicle was commercialized by the private auto-manufacturers in an arrangement with the government. In the later stage, privately-owned CTC, plus the public-private partnership of federal universities and industry, academic center Instituto Agronomico de Campinas and privately-owned Cana Vialis all contributed to seed and sugar productivity gains. Mechanization was driven by sugar

In Denmark, innovations and adaptations were cross-sectoral and included developments emerging from both government and civil society (Chapter 5). Policies were favorable, generally from the late 1970s to 2000 at which point the renewable energy policy regime disappeared considerably. Among the innovations and adaptations were continuous wind technology enhancements informed by broadly recognized feedback from turbine users, manufacturers and the Risoe laboratory. The application of local cooperative ownership models to community wind power projects and early-stage grid integration by utilities reflect other wider-ranging technology and organizational developments which began in the early period. Within government, the use of methods like one-stop permitting streamlined development and has increasingly been adopted elsewhere. Interestingly, when a sharp governmental shift eliminated almost all support for wind development in the period from 2001-2007, wind technology and analysis advances by industry and the Risoe laboratory as well as grid and power market adaptations continued.

In France, the government was fundamentally involved in all relevant innovations and adaptations since the actors driving most innovations were public employees (Chapter 6). Key developments arose from industry and research centers, namely state-owned EDF, Areva (and its predecessors), and CEA. These developments included changes in reactor design, size and early safety features; load-following and MOX use; as well as the build-out o the fuel cycle. More recent safety modifications and reactor design changes are linked closely to governmental safety directives, EDF, and Areva in

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mill technicians, manufacturers, and research institutes. The commercialization of flex fuel was led by the auto-manufacturers.

partnership with Siemens. Policy support, often in the form of outright action, rather than codified measures, was generally constant throughout the period and favoring nuclear energy.

In Iceland, relevant innovations and adaptations can be traced to government, industry, research labs and civil society (Chapter 7). During the early period of scale-up, localities' pursuit of geothermal assessments and infrastructure combined with work by the state actor, National Energy Agency (NEA), spurring countless adaptations in exploration methods. In conjunction with these, the energy industry adapted drilling, site engineering, and process re-design at times directly partnering with the NEA. Resource parks and industry spillovers evolved incrementally and were led largely by industry anticipating or responding to civil society interest. Policies were mostly favorable with some early limitations in energy company charters that have since been relaxed.

In sum, innovations and adaptations that were fundamental to the four energy system transitions emerged from industry and research centers, often supported by public funds, but also from less traditional sources like public policy-makers and civil society. Even in cases where public actors implemented energy transitions, the technology and institutional innovations which propelled the transition often stemmed from partnerships of various kinds. Governmental influence was significant during many periods, albeit in varying degrees and forms, ranging from funding of basic research to formulating and maintaining coherent policies.[11]

E. DRIVERS and BARRIERS

The cases of this study revealed a limited number of commonly shared drivers and barriers.

Among the common and prominent drivers were: the pressure to reduce oil imports and increase national energy security; the related aim to protect the balance of payments from oil price volatility; and the goal to improve environmental conditions or, at least, reducing adverse environmental impacts. Specific to energy security and oil import reductions, such aims were raised consistently in the interviews. The dramatic drop in oil prices in 1986 appeared to have temporarily reduced societal concern in this regard, but the concern reappeared, when prices rose. The desire for energy self-sufficiency also factored in all four countries, but the level of this varied, particularly for countries, like Brazil, which became a net energy exporter. Closely tied to energy security and oil import drivers was the corresponding aim of protecting the national balance of payments, shown to be sensitive in all cases.

Concerns about the environment were evident in all the cases and were more varied – serving as drivers and barriers of the energy transitions. Among the drivers, for example, urban air pollution, the desire to reduce waste or encourage conservation,

[11] This study considered sectoral contributions of actors who innovated in addition those who communicated needs that, in turn, led to innovation. Further research could differentiate these channels more fully.

along with worries about climate change propelled adoption of low carbon energy technologies. In Iceland, for instance, the early 20th century move toward geothermal energy for space heating was recognized for reducing coal-fired pollution. This insight, combined with interest in clean energy, factored in its later transition. Early support for wind power in Denmark was associated with public concern about nuclear waste, radiation and broader safety issues. This same set of concerns challenged French nuclear development, although limited opportunities for public engagement counterbalanced its effect.

Among barriers, uncertainty was observed in all the cases. In Brazil, for example, uncertainty associated with policy, supply, and investment existed after the ethanol program was phased out in the early 1990s, and when fuel supply shortages occurred. More recently, the artificial subsidizing of Brazilian gasoline prices as an inflationary policy skews market dynamics, creating uncertainty for investors in market-competitive ethanol. In Denmark, uncertainty was most evident in the period from 2000-2007, when a series of policy shifts and diminished support signaled changed priorities vis-a-vis wind energy adoption. In France, some uncertainty remains today in relation to President Hollande's plans for the nuclear program, how long-term waste will ultimately be managed, and whether the industry will thrive in an ambivalent global market. Finally, in Iceland uncertainty manifests in less overt ways in drilling and resource assessments, as well as questions about projects like the sub-sea cable.

When considering generalizations across the four cases, the shared drivers and barriers do not sufficiently explain, for example, the flux in the different transitions. Without question, more idiosyncratic drivers and barriers account for some explanatory strength. Yet, intervening variables or pre-conditions also carry weight in this regard.

F. PRE-CONDITIONS in the ENABLING ENVIRONMENT

This study evaluated seven pre-conditions having materiality in terms of energy transitions. These include the instrumentality of public actors; policy aptness; country-level readiness for change; institutional capacity; effects of strong networks; the historical familiarity of a technology for a society; and the conduciveness of a given energy technology for a specific society. The first four pre-conditions were found to have particular resonance with the cases of this study and are discussed below. The first three in the above list had the strongest explanatory strength.

The instrumentality of public actors was pre-condition that was observed in all the cases studied. As noted earlier, cross-sectoral contributions played a role, however public actors filled many important gaps and often engineered or led the change. In Brazil, for example, state-owned Petrobras facilitated the integration of ethanol into the supply chain, while development banks, like BNDES, provided early financing to modify distilleries and the auto-manufacturing lines. With the French energy transition, state-owned EDF, Framatome/Cogema/Areva, and CEA led the development of nuclear power plants and the nuclear fuel cycle in addition to the R&D underpinning technical redesign. In the case of Iceland, state-owned Landsvirkjun, as well as municipally-owned Reykjavik Energy and Hitaveita Sudurnesja, were among the key public actors which developed and managed the necessary energy production and delivery systems. In addition, the Icelandic National Energy Agency was integral in identifying and advising on resources. In Denmark, municipally-owned utilities were early, albeit at times reluctant enablers. Now, state-owned grid operator Energinet, the DEA and the Wind Secretariat manage key lines of wind power development in a manner which allows continued scaling. In each case, public actors have not only played critical roles in policy implementation, but in some cases they have been innovators or decision-makers behind energy system change. What they share is a legislative mandate. Who defines how the mandate will be implemented appears to be case-specific.

The aptness of policy is another crucial pre-condition for explaining energy system change. Here, the appropriateness of policy fit is often assumed within discussions of policy formulation and design. However, in practice, policy aptness may become secondary to the power politics and institutional capabilities which underpin the policy subsystems (Simon, 1968; Cahn, 1995; Kingdon, 1995; Lowi, 1979; Galston, 2006; Immergut, 2006). This concept of aptness cuts across ideas on adaptiveness and multiple objectives (Howlett et al, 2009); context (Rist, 1998; Schon, and Rein, 1994); and national characteristics[12] (Arentsen, 2005; Bobrow, 2006; Freeman, 1985; Linder

[12] National institutions, for example, can differ with varied concentrations of power in consensus and majoritarian democracies (Adam and Kriesi, 2007, citing Lijphart (1999). Interaction patterns then are likely to be more cooperative in the consensus-based democracies and more competitive in the majoritarian ones (Adam and Kriesi, 2007). Denmark exemplifies a consensus-based model, whereas the French model is more majoritarian-based (Ibid).

and Peters, 1989).[13] When governments prioritize stability, longevity and coherence of policy in the context of meeting challenging objectives over longer tracts of time, policy aptness may be implicitly or explicitly recognized (OECD, 2012; Hamilton, 2009; Centre for European Policy Studies, 2008; Sawin, 2004a and 2004b). For the purposes, here, policy aptness refers to an appropriateness for conditions and goals as well as other policies. Importantly, policy aptness was not always constant in the cases of this study. It is here where some of the underlying coherence of energy trajectories becomes more clear.

In the cases of Iceland and France, policy aptness manifested in the direct and often rapid intervention of public actors, as they built out or improved the existing energy systems during urgent times. When Icelandic energy-economic goals were challenged, for example, in the late 1990s/early 2000s with climate change concerns, the government secured special Kyoto Protocol allowances. This policy intervention could have occurred at different points (and still constituted policy adaptiveness), yet it occurred in a fairly timely and apt manner for conditions on the ground. Similarly with France, when public concern over waste management reached a level of urgency in the late 1980s, the government instituted new measures of review and research in short order.

For Denmark, Chapter 5 showed how incremental policy changes were typically well-attuned to prevailing needs. Such needs were also closely tied to overarching goals of

[13] Other elements could include feasibility, actor capability, etc.

energy diversification, self-sufficiency and industrial development for much of the period. As conditions shifted unfavorably in the international wind power market and with local challenges, for example, the government responded to reinvigorate growth with guaranteed projects and improvements in planning.

With Brazil, objectives to reduce foreign oil dependence and balance of payment flux were met quite quickly as shocks from the oil crisis reverberated. The very robust formation of an ethanol market with the ProAlcool program reflected a close syncing of policy approach with broadly-based energy and economic needs. However, one could argue that the dismantling of Proalcool was not apt for continued growth in biofuels in the 1990s.[14] A retrenchment in the market ensued, showing how policy 'inaptness' for biofuels purposes can contribute unfavorably, as policy aptness can contribute favorably.

Perhaps what is more revealing in the Danish and Brazilian cases, is that new energy markets can sustain (in more 'lean form' for a while) when policy aptness is lacking, if the markets have attained a certain threshold of viability. For both cases, new growth was stymied for a period. However, continued problem-solving by industry and research labs, enabled new innovation and efficiencies to be attained.

Another often cited pre-condition for successful energy system change is institutional capacity, or the ability of organizations and their networks to serve societal needs.

[14] The dismantling of ProAlcool may have been apt for other (non-energy) policy objectives and conditions.

Institutions can be fairly well-defined, as with an electric power market, or less so, as with local cooperatives. Institutional roles can also vary with some providing risk-sharing protection, connectivity, or incentive structures (Jacobsson and Johnson, 2000). Such institutional capacities may shape a technology pathway (Edquist and Johnson, 1997). In Brazil, for example, Instituto do Acucar e do Alcool (IAA) buffered sugar producers from international market forces and was behind some technology modernization up to the 1990s (Sachs et al, 2009). The collective efforts of IAA, Planalsucar, Copersucar and the auto industry's ANFAVEA also ensured that industry issues were addressed at least on some level. In Denmark, cooperatives provided an early and very important means for guiding the modern uptake of wind power technology. These groups not only mitigated financial risk, but served as a locus for learning and promoted societal acceptance. In France, widespread deference to the institutions of senior civil servants and groups like the Corps de Mines appear to have been key for the robust and continued French nuclear trajectory. Finally in Iceland, the deep involvement of the National Energy Agency, the Iceland Survey, and their predecessors in geothermal energy development were fundamental for knowledge generation, policy development, and guidance. From each of these cases, institutions certainly mattered, yet this point can be extended.

Linked to the condition of institutional capacity is the concept of readiness to undertake an energy transition. Readiness combines the above institutional capacity with indigenous expertise and the existence of some level of adequate infrastructure and/or markets. National decision-makers in all the countries studied were caught off-guard by the speed and impact of the oil price shocks. Nonetheless, three of the four countries were able to rapidly mobilize with low carbon energy sources. The shocks spurred action and a surge in capacity, or what Albert Hirschmann calls 'slack' (1970).

Among the quick-to-mobilize countries were Iceland and France. Since they each had existing low carbon energy paths, they did not need to allocate significant start-up time and effort to establish new technology, expertise and markets. They extended existing capacity, allowing them to substitute one energy source for another. This points to the rather obvious truism that having appropriate institutions and expertise in place to begin or amplify a transformation, increases the chances of its success.

The case of Brazil offers added insight on the idea of readiness. Like France and Iceland, Brazil was able to scale up rapidly from niches and other markets, even though ethanol use was negligible in the period immediately prior to the first oil shock. What mattered was the presence of resources, institutions, systems, and a plan – even if they were in place for other purposes. The precondition of readiness overlaps with the idea of nimbleness, but goes further by requiring the necessary 'architecture', meaning the necessary resources and systems to be in place. When disruption occurs, whether economic, geo-political, or even weather-related, readiness allows actors to quickly seize or create opportunity for change. The essence of readiness resonates with an idea attributed to Benjamin Disraeli that the secret to success is being ready when an opportunity arises.

G. WERE the PRIME MOVERS DETERMINISTICALLY DRIVEN to SHIFT?

There is a tendency to superficially treat countries, like those described in this study, as naturally endowed with indigenous resources, so their adoption of certain kinds of energy is pre-determined. It is certainly true that Iceland has substantial geothermal energy potential and the tropics of Brazil are well-suited for sugarcane production. Yet the mere existence of these resources can in no way explain why and how the transitions to low carbon energy were so fully effectuated, or when they were.

In Brazil, the scale-up was far from pre-determined and did not emerge naturally. A proposal to expand ethanol production had been in place prior to the first oil shock, yet was not implemented. When the ProAlcool program was launched, countless individual initiatives in the sugarcane, transport fuel and auto sectors had to be developed and coordinated. Furthermore, significant retrenchment occurred when policy support subsided in the 1990s, showing other forces were at play.

Like Brazil, the scale-up of geothermal energy in Iceland was neither deterministic nor certain. Nothing shows this more clearly than the fact that geothermal heating was competitive in the 1970s, but was utilized by less than half the population. Greater knowledge of energy resources, improved financing, and action of public actors were all necessary.

France and Denmark did not even begin with a relative advantage in natural resources. France imports uranium (and developed indigenous reprocessing), although in an earlier time the resource was mined domestically. Denmark has some good wind potential, but not to the extent of its neighbor Scotland (Troen and Peterson, 1989; Interviews, 2011-2012), which has not progressed as far with wind power. When the additional layers of decision-making, organizational learning and system development are added, it is clear that these national energy transitions were far from pre-ordained.

Other countries may find they are unable to transform their national energy systems with these specific energy technologies. However, such countries may have potential and strengths related to other energy technologies. Here, the take-away for policy-makers is that one needs to make optimal use of the resources available.

H. IMPLICATIONS of the FINDINGS

The findings of this study allow certain inferences to be drawn in relation to prevailing ideas and literature.

First, the timescales for energy transformation show that sectoral level energy change within a country can robustly shift by 20-50% in 10-15 years. Using linear (non-logistic), substitution analysis of energy balances, this research found that in just ten years between 1975 and 1985, for instance, France altered its electricity mix from 10% to 65% nuclear energy (OECD/IEA, 2012). In under 15 years, Iceland shifted its space heating coverage from 43% to 83% of the population with geothermal energy during the time between 1970 and the mid 1980s (Chapter 7). In that same period, Iceland's total primary energy shifted from 31% to 53% geothermal energy (OECD/IEA, 2012). Each of these shifts was marked by infrastructural modifications.

This complements developing work on industry level scaling of energy technology (Wilson, forthcoming) and differs from views that energy system change requires long periods. Previous efforts to characterize and predict energy substitution, using coupled logistic equations, indicate that such shifts are typically multi-decadal and often require 50-100 years (Marchetti, 1977; Marchetti and Nakicenovic, 1979).[15] Yet within such work, examples of rapid scale-up of oil, gas and nuclear energy at the country and sectoral levels for earlier periods resonate with what was found in low carbon shifts of this study (Marchetti and Nakicenovic, 1979). Since countries have institutions and cultures that can be transformed much more easily than forces at a global level, this is insight should not be entirely surprising. National decision-makers should consider energy shifts utilizing 5-15 plans.

Second, with respect to factors influencing rates of technology diffusion, complexity can present challenges without impeding the energy transition. In this study, nuclear technology was arguably the most complex technology of the four studied. However, French adoption was also the most rapid and robust. Speculation on the delimiting nature of complexity is perfectly reasonable (Rogers, 1995; Grubler, et al; 1999; Grubler, 2010, referencing Lovins, 1986; Grubler, forthcoming), yet this study showed there are other intervening factors, like the pivotal inputs of public actors; policy aptness; the readiness of the system to change (including indigenous experts); and,

[15] Marchetti and Nakicenovic's analysis generalized Fisher and Pry's two parameter logistic function (1971; Grubler forthcoming, citing Fisher and Pry, 1970) to examine technological substitution across more than two competing technologies. With this, Marchetti and Nakicenovic tested times required to shift the market share for a particular energy type from 1 to 50%, in other words to become the dominant fuel (1979).

perhaps arguably, societal deference (Chapter 6), which can overcome the inertial effect of technology or system complexity. If supported by subsequent studies, this finding could have immense relevance for policy-makers and planners focused on energy transformation. The willingness and capacity of government to take on the most relevant role, and societal buy-in or deference, may need to be given much greater attention than in the past.

Third, turning to factors which *accelerate* diffusion, this research confirms the importance of pre-existing niche markets (Grubler et al, 1999; Grubler, forthcoming; Smith and Raven, undated; Geels and Schot, 2007; and Kemp et al, 1998; Wilson, forthcoming). This finding dovetails not only with the earlier discussion of readiness as a precondition, but also with the energy transition framework that was introduced.

These findings also offer new ways of thinking about a country's nimbleness and the inertial effects of established infrastructure in the context of adaptive or absorptive capacities (Smil, 2010; Porter, 1990; Henderson and Newell, 2010/2011). In Brazil and France, for instance, traditional infrastructure was augmented to *facilitate* change, rather than encumber it. Given this, theory on infrastructural inertia should be qualified, indicating that established infrastructure is not necessarily a barrier to change. If suitable for adaptation, established infrastructure could be leveraged to enhance it. Naturally, a wider pool of countries with more varied systems will need to be examined to substantiate this. As for the idea that determinants of transition rates are likely to differ over time (Grubler, 1997, Rogers 1995), this study fully bears this out.

Finally, the economics of energy system change have some rather telling insights. Conversions to low carbon energy can begin with a focus on new energy technologies that are not cost competitive, but can become competitive over time. Brazilian ethanol, French nuclear power, and Icelandic geothermal-based electricity are now competitive. They weren't at the outset.

This understanding is in marked contrast to the thinking underpinning least-cost economics which are often the principal criterion in energy planning, and a historical model for investment by public utilities (American Academy of Arts and Sciences/AAAS, 2011). Efficiency is, without a doubt, a powerful rationale, yet it can cause countries to overlook wider objectives and co-benefits such as built-in adaptability in otherwise irreversible infrastructure decisions, industrial development, environmental stewardship, enhanced public health, and achieving energy sustainability. Interestingly, each country of this study evidenced clear improvements in its human development trends, as well as co-benefits like industry development, as it was scaling low carbon energy (UNDP, 2012).

I. IMPROVING PREVAILING KNOWLEDGE of LOW CARBON ENERGY TRANSITIONS

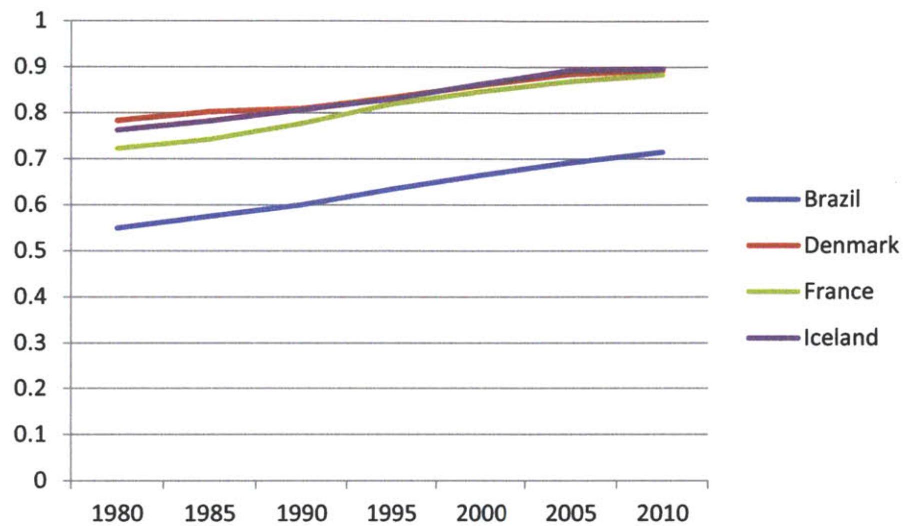
This study presented a new, conceptual framework for assessing national energy system transitions, highlighting three different approaches -- establishing new systems, reconstituting existing ones, or ramping them.

Among the four cases, substantial transformations in energy balances toward low carbon energy were found to occur in very short periods with attendant gains in cost reductions, industrial development, and quality of life improvements. The dynamics of societal acceptance were also found to be important, although findings were not definitive. Innovations and adaptations in all cases occurred cross-sectorally. This study also showed that public actors and policy can be pivotal in filling critical gaps, and in leading or channeling change. Moreover, a country's readiness to enable such system change can also prove to be vital, particularly when paired with apt policy.

The following chapter builds on the findings of this chapter with a discussion of policy implications and areas for further research.

APPENDIX

Figure A1: International Human Development Indicators



Source: UNDP, 2012.

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Chapter 9

Lessons and Areas for Further Research

There is an old adage that history is about revolution and evolution.[1] This study offers insight into that notion with respect to the ways that national energy pathways emerge and disruptively or incrementally progress. This research examined such change in the context of different prisms, including determinants (positive, negative, and intervening) and indicators of a transition's performance and durability. In doing so, a conceptual framework of models was presented along with and taxonomy of energy transition classifications.

This chapter discusses some key lessons related to the adoption of new technologies and scaling of preferred energy. It also highlights areas for further research.

A. LESSONS

While there is no generic formula for shifting to low carbon energy (or undertaking an energy transition, for that matter), this study was able to take some stock of how to engage the phenomenon. Whether transitions emerge or are driven, there is room for strategic channeling.

[1] The 19th century inventor of the fountain pen (US Patent 230706) Lewis Korns wrote, "The history of the human race always has been, and most likely always will be, that of evolution and revolution" (Undated).

- **Role of government:** Given the widely entrenched nature of national energy systems and the public goods aspects of many energy-related challenges, government has a clear role to play in the energy domain. Irrespective of how a transition emerges, public actors and policy can be instrumental in the identification and bridging of gaps at pivotal junctures in a way that no other may adequately address.[2]

- **Market mechanisms vs. deployment:** Societal views about governing domestic natural resources will factor in whether an energy transition depends largely on markets, government, or other means. Absent urgently perceived circumstances, societies which are heavily or traditionally reliant on market-based approaches may choose to focus on structuring incentive mechanisms in line with broader aims, and in doing so provide adequate signals that create value. Market mechanisms are, of course, not the only or necessarily the optimal way to effectuate change. Deployment can often be more quickly carried out by initiating the shift with public actors. This latter approach syncs with centrally planned societies and conditions warranting rapid and concerted response.

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[2] This resonates with theory on collective logic which tells us that individuals, working toward their own gains and acting in isolation, are unlikely to meet public goods objectives, even if it is to their own benefit (Olson, 1965). Going further, theory on appropriability suggests that actors won't likely pursue research and investment for some of the most perplexing societal challenges, if the ability to capture all the benefits of broadly-applicable results is less likely (Dosi et al, 2006; Anex, 2000). For both cases, governmental intervention can be instrumental.

- **Cultivating agility:** Effective and lasting change are not always synonymous in energy transformations. Well-conceived policy is often crucial, if efficacy and durability are desired. This means building flexibilities into a system to strengthen readiness for response to new conditions and learning. Fostering agile institutions and public actors can go a long way in this regard. Additionally, measures, like pre-determined points of review and setting upper and lower bounds with triggers for action, can allow for strategic corrections.

- **Pluralities of interest**: Cooperative pluralism should not be under-estimated. Alignment of multiple interests across sectors, industries, and/or diverse constituencies provides not only the opportunity for synergy, but a basis on which to extend buy-in and learning.

- **Windows of opportunity**: Focusing events, like oil shocks, can provide windows of opportunity for rapid mobilization and the launch of an energy transition, despite differences in views. However, such windows have a limited shelf-life at which point more common tensions between competing interests will re-emerge and can undermine progress. Here, important traction, such as from cross-sectoral learning, can cohere larger interests.

- **Lead times for energy transitions**: Lead times of roughly 5 years were seen in some of the cases of this study, at which point new and significant scaling of preferred energy was well underway. Countries which adopt or develop novel technologies and markets can anticipate longer gestation time to build expertise, infrastructure and institutions relative to those which are primed for change. Yet, the pace of scale-up may be accelerated with strategic leveraging of public actors and policy.

- **Costs and benefits of change:** Least cost economics in energy decision-making carries a widely recognized level of significance, yet this study shows that policy-makers can justifiably go beyond this analytical benchmark to account for objectives and gains that extend outside the simplified domain of near-term costs. Opportunities for a wider set of co-benefits, including the flexibility to adapt in otherwise irreversible decisions, can be prioritized in conjunction with an energy transition. Such benefits may be difficult to value in planning and analysis, but warrant full integration in decision-making and societal discourse.

- **Problem-solving and adaptation**: Advances in technology, process, practice and institutions can be inputs as well as outputs of energy system transformation. While the timing and nature of such developments are not entirely predictable, it is well within policy-makers' gambit to encourage widespread problem-solving by: informing about resource options/availability in the context of issues; supporting demonstration; mandating certain areas of necessary change; and taking some critical action. Ensuring that channels for communication are in place and widely-known during market mobilization, for instance, can allow critical and timely address of developing insights. As with challenges to most societal complexities, policy-makers also have the opportunity to foster change by example, demonstrating learning, and granting legitimacy.

In short, none of the early actors behind the energy transitions of this study could have anticipated the full totality of developments which would follow. This speaks to a larger take-away, that experimentation is a fundamental aspect to effectuating a desired energy transformation. Such trial and error applies not only to technologies and systems, but policies and practices as well. If learning and uncertainty are understood to be an intrinsic part of fuller progress, then widespread problem solving, rather than reactionary protectionism might bring greater strengths to bear.

B. AREAS for FUTURE RESEARCH

This research considered energy transitions in four countries, with four technologies, and for essentially four decades. It was by no means comprehensive and represents a step into an emergent field with plenty of important ground yet to be explored.

The following highlights a number of additional vectors to explore. First, theoretical insights that emerged in this study on technology complexity and limits, varying maturities of technology and markets, dual purposes of technology and industries, and the adaptation of established infrastructure all offer rich areas for further exploration with a wider pool of cases. Moreover, parallel lines of questions could consider the role of financing structures, natural monopolies, and market power; the politics of transition costs; and varying approaches to resource management in energy system adaptation.

New cases could test and extend the analytical tools that were introduced or the explanatory strength for determinants of change. Promising cases include: geothermal energy conversions in Kenya, the Philippines, Indonesia, and Cost Rica; shifts with energy efficiency in Japan; and transitions to solar thermal water heating in countries along the Mediterranean. With further progress in substitution, cases like solar photovoltaic energy in Germany, also hold potential for added insight. One could contrast energy transitions spurred by focusing events, like the Chernobyl accident, relative to ones more closely linked to technological discoveries. Research could also consider energy trajectories in supra-national regions or look at parallel changes of two energy forms (i.e. a renewable and non-renewable form of energy) within one country.

Other promising research includes the conduciveness of certain technological system attributes (i.e. centralized versus decentralized applications of energy) for varying adoption patterns. More systematic analysis is also warranted on the economics, politics and institutional elements of energy system change. Naturally, alternative levels could be more fully examined at the local and global level. Finally, the framework and taxonomy used in this study could be tested and refined in different industries, like biotechnology or communications.

C. FINAL TAKE-AWAY

National energy system transitions, like change itself, can be pro-active or reactive. While transformation can occur at times in response to challenging circumstances, a window of opportunity exists to not only optimize an energy mix, reduce environmental effects and encourage industries, but to advance society itself.

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Acronyms and Abbreviations

AC	Alternating Current
ACEEE	American Council for Energy Efficient Economy
ACIA	Arctic Climate Impact Assessment
ACRO	American College of Radiation Oncology
AFNI	Agence France Nucleaire International
ANDRA	L'Agence Nationale pour la Gestion des Dechets Radioactifs
ANEEL	Agencia Nacional de Energia Eletrica (Electric Energy National Agency)
ANFAVEA	Associacao Nacional dos Fabricantes de Veículos Automotores
ANP	Agencia Nacional do Petroleo (National Petroleum Agency)
ASN	Autorite de surete nucleaire
ATV	Academy of Technical Sciences
AWEA	American Wind Energy Association
BBA	Bolsa Brasileira do Alcool (Brazilian Alcohol Exchange)
BBC	British Broadcasting Company
BC	Before Christ
BCE	Before the Common Era
B-D-K-T	Bupp-Derian-Komanoff-Taylor hypothesis
BEN	Balanco de Energia Nacional
BM&F	Bolsa Mercantil E Future (Mercantile and Futures Exchange)
BNDES	Banco Nacional de Desenvolvimento Economico e Social (National Bank of Economic and Social Development)
BP	Formerly British Petroleum; BP is now the name
BRL	Brazilian Reais
BWR	Boling Water Reactors
CANDU	Canada Deuterium Uranium
CANGEA	Canadian Geothermal Energy Association
CCS	Carbon Capture and Sequestration
CEA	Comisariat a l'energie atomique
CEAF	Centro de Analise Funcional e Aplicações
CEIB	Inter-ministerial Executive Commission (Brazil)
CENELEC	Euro Committee for Electro-technical Commission
CENPES	Centro de Pesquisas (Research Center)
CEPAL	Comissao Economica para a America Latina e o Caribe (Economic Commission for Latin America and the Caribbean)
CEPEA	Centro de Estudos Avancados em Economia Aplicada
CEPN	Centre d'Economie de l'université Paris
CEPOS	Center for Political Studies
CETESB	Companhia Ambiental do Estado de Sao Paul (Environmental Agency of the State of Sao Paulo)
CFDT	French Democratic Confederation of Labor
CGEE	Centro de Gestao e Estudos Estrategicos (Center for Management and Estrategic Studies)
CGP	Commissariat General du Plan
CHP	Combined Heat and Power
CIA	Central Intelligence Agency
CIVICUS	World Alliance for Citizen Participation
CNDP	National Commission on Public Debate
CNE	National Commission on Evaluation
CNEF	The Nuclear Financing Committee
CNPB	Conselho Nacional de Petroleo Biocombustiveis (National Council for Biodiesel)

CNPE	Conselho Nacional de Politica Energetica (National Council for Energy Policy)
CNRS	French Scientific Research Center
CNRS	Centre national de la recherche scientifique
CO	Carbon Monoxide
CO2	Carbon dioxide
COD	Concerted Offshore Wind Energy Deployment
COFINS	Contribucao para o Financiamento da Seguridade Social
COP3	Conference of Parties 3
Copersucar	Sugar alcohol cooperative
COPPE-UFRJ	Centro de Pos-graduacao e Pesquisa de Engenheiria
CPTEC/INPE	Centro de Previsao de Tempo e Estudos Climaticos - CPTEC/INPE
CRIIRAD	Commission de Recherche et d'Information Independantes sur la Radioactivite (French Radiation Monitoring Agency)
CRS	Congressional Research Service
CSSIN	Council for Nuclear Safety and Information
CTA	Centro Tecnico Aeroespacial (Aerospace Technical Center)
CTBE	Laboratorio Nacional de Ciencia e Technologia do Bioetanol (National Laboratory for Bioethanol Science and Technology)
CTC	Centro Tecnico Canavieiro (Sugarcane Technical Center)
DANIDA	Danish International Aide Agency
DC	Direct Current
DEA	Danish Energy Agency
DGEC	Direction Generele de l'Energie et du Climat
DGSNR	Directorate General for Nuclear Safety and Radiation Protection
Dkk	Danish Krona
DMCE	Danish Ministry of Climate and Energy
DOE	Department of Energy
DOS	Department of State
DTU	Technical University of Denmark
DWIA	Danish Wind Industry Association
DWMA	Danish Wind Manufacture Association
DWTO	Danish Wind Turbine Owners
EAEM	Energy and Environmental Management
EC	European Comission
EDF	Eletricite de France
EEA	European Economic Agreement
EEC	European Economic Community
EFTA	European Free Trade association
EGS	Enhanced Geothermal Systems
EIA	Energy Information Administration
EJ	Exajoules
EMBRAPA	Brazilian Agricultural Research Corporation
EPA	Environmental Protection Agency
EPE	Empresa de Pesquisas Energeticas (Energy Research Company)
EPR	European Pressurized Reactor
EPRI	Electric Power Research Institute
ERI	Energy Research Institute
ESMAP	Energy Sector Mgmt Assistance Program
EU	European Union
EURODIF	French Nuclear Fuel Consortium
EV	Electric Vehicles
EWEA	European Wind Energy Association

EWETP	European Wind Energy Technology Platform
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Statistics
FAPESP	Fundacao de Amparo a Pesquisa do Estado de Sao Paulo
FBR	Fast Breeder Reactor
FF	Flexible Fuel
FGV	Fundacao Getulio Vargas (Getulio Vargas Foundation)
FIT	Feed in Tariff
FX	Foreign Exchange
GDP	Gross Domestic Product
GEA	Geothermal Energy Association
GHG	Greenhouse gases
GJ	Gigajoules
GM	General Motors
GSIEN	Radiation Safety Authority
GtCO2	Gigatons of Carbon Dioxide
GTOE	Gigatons of Oil Equivalent
GTZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GWEC	Global Wind Energy Council
H/C	Hydrocarbons
HAWT	Horizontal Axis Wind Turbine
HEV	Hybrid Electric Vehicles
HTR	Heater
HVDC	High Voltage Direct Current
HWR	Heavy Water Reactor
IAA	Instituto do Alcool e do Acucar (Alcohol and Sugar Institute)
IAEA	International Atomic Energy Agency
IBGE	Instituto Brasileiro de Geografia e Estatística (Brazilian Institute of Geographics and Statistics)
ICE	Internal Combustion Engine
ICPE	Installations classees pour la protection de l'environnement
IDDP	Iceland Deep Drilling Project
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGCC	Integrated gasification combined cycle
IGOs	Intergovernmental Organizations
IIASA	International Institute of Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRSN	Institut de Radioprotection et de Suret Nucleaire
IRSN	Institute for Radiation Protection and Nuclear safety
ISEA	International Sustainable Energy Assessment
ISK	Icelandic Kroner
ITA	Instituto de Tecnologia Aeronautica
kW	Kilowatts
LNG	Liquefied Natural Gas
LOGIT	Logistic regression
LPG	Liquefied Petroleum Gas
LWR	Light Water Reactors
MAPA	Ministerio da Agricultura Pecuaria e Abastecimento (Ministry of Agriculture, Livestock and Supply)
MBOE	Million Barrels of Oil Equivalent

MCT	Ministerio da Ciencia e Tecnologia (Science and Technology Ministry)
MEEDDM	Ministry of Ecology, Energy, Sustainable Development and the Sea
MIC	Ministerio da Industria e Comercio
MIT	Massachusetts Institute of Technology
MME	Ministerio de Minas e Energia (Ministry of Mines and Energy)
MOX	Mixed Oxide
MLPs	Multi-Level Perspectives
MSR	Moisture Separator Reheater
MTBE	Methyl tert-butyl ether
MWh	Megawatts/hour
NATO	North Atlantic Treaty Organization
NEA	Nuclear Energy Agency
NEF	New Energy Finance
NES	National Energy System
NGOs	Non-governmental Organizations
NHMRC	National Health and Medical Research Council
NICs	National Innovative Capabilities
NOAA	National Oceanic and Atmospheric Administration
NOx	Nitrogen Oxide
NPP	Nuclear Power Plants
NRC	Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
NSI/NIS	National Systems of Innovation/Notional Innovation Systems
NU	Natural Uranium
NUGG	Natural Uranium Gas Graphite
O&M	Operations and Maintenance
OECD	Organization of Economic Cooperation and Development
OOA	Organization for Information about Nuclear Power
OPEC	Organization of Petroleum Exporting Countries
OVE	Organization for Renewable Energy
OVEG	Brazilian Biofuel Program
PA	Precision Agriculture
PBS	Public Broadcasting System
PCAST	President's Council Advisors on Science and Technology
PD	People's Daily
PEON	La Commission pour la Production d'Electricite d'Origine Nucleaire
PIS/PASEP	O Programa de Integracao Social (PIS) e o Programa de Formacao do Patrimonio do Servidor Publico (PASEP)
PIZ	Presurizer
PNPB	Programa Nacional do Petroleo e Biocombustiveis
PPI	Pluri-annual Investment Plan
PPIAF	Public-Private Infrastructure Advisory Facility
PPP	Public-Private Partnership
PRIS	Nuclear Reactor Database (IAEA)
PSO	Public Shared Obligation
PURPA	The Public Utilities Regulatory Policy Act
PWR	Pressurized Water Reactors
R&D	Research and Development
RBMK	Reaktor Bolshoi Moshchnosti Kanalye
RCP	Reactor Coolant Pump
RD&D	Research Development and Demonstration
REC	Renewable Energy Credit
REE	Red Eletrica de Espana

REN	Renewable Energy Network
RET	Renewable Energy Technology/Renewables
RETD	Renewable Energy Technology Deployment
RHR	Residual Heat Removal
RIDESA	Rede Intrauniversitaria para o Desenvolvimento do Setor Sucroenergetico (Interuniversity Network for the Development of the Sugar-Energy Sector)
RTE	Reseau Transport d'Electricite
S/G	Steam Generator
SAP	Software Application Program
SCPRI	French Radiation Protection Agency
SEA	Strategic Environmental Assessment
SITC	UN Comtrade Classification
SO2	Sulfuric Oxide
SOE	State Owned Enterprise
SRREN	Special Report on Renewable Energy
TELESP	Telefones de Sao Paulo
TFC	Total Final Consumption
TGV	Train de Grand Velocite
TMI	Three Mile Island
TOE	Tons of Oil Equivalent
TOTVS	Corporate Social Network
TPES	Total Primary Energy Supply
TSO	Transmission System Operator
UCS	Union of Concerned Scientists
UFMG	Universidade Federal de Minas Gerais
UK	United Kingdom
UN	United Nations
UNCRET	United Nations Centre for Natural Resources, Energy and Transport
UNDEP	United Nations Development Program
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNGG	Uranium Naturel Graphite Gaz
UNICA	Uniao da Agroindustria Canavieira de Sao Paulo (Sao Paulo Sugarcane Agroindustry Union)
UNICAMP	Universidade de Campinas
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UNU	United Nations University
US	United States
USDA	US Department of Agriculture
USGS	US Geological Survey
USP	Universidade de Sao Paulo
USSR	Union of the Soviet Socialist Republic
VAWT	Vertical Axis Wind Turbine
VIC	Vertically Integrated Company
VW	Volkswagen
WCED	World Comission on the Environment and Development
WCRE	World Council for Renewable Energy
WDI	Would Development Indicators
WEA	Wind Energy Association
WEC	World Energy Council
WIPO	World Intellectual Property Organization
WNA	World Nuclear Association
WWF	World Wildlife Fund

Interviews/Communications: Brazil

***Note: Multiple interviews/communications*

Individual		Institution		Dates
Arouca	Mauricio	Instituto Alberto Luiz Coimbra de Pos-Graduacao e Pesquisa de Engenharia (COPPE)		November 23, 2010
Barroso	Luis	PSR, Electricity and Natural Gas Consuting and Technical Services		June 29, 2012
Braunbeck	Oscar	Laboratorio Nacional de Ciência e Tecnologia do Bioetanol (CTBE)		November 18, 2010
Carvalho	Arnaldo	Inter-American Development Bank		April 27, 2011
Cunha	Marcelo	Laboratorio Nacional de Ciência e Tecnologia do Bioetanol (CTBE)	**	November 18, 2010-November 24, 2010
Dias	José Manuel Cabral	Embrapa Agroenergia		December 3, 2010
Dornelles	Ricardo	Ministerio de Minas e Energia (MME)		December 3, 2010
Fernandes	Joao Lucio	Operador Nacional do Sistema Elétrico (ONS) (National Electricity System Operator)		December 8, 2010
Filho	Paulo	Banco Nacional de Desenvolvimento Economico e Social (BNDES)		November 25, 2010
Filho	Livio	Ministerio de Minas e Energia (MME)		November 6, 2010
Fontes	Sergio	Petróleo Brasileiro S.A. (Petrobras)	**	December 19, 2011-December 26, 2011
Garnero	Mario	Formerly, Associação Nacional dos Fabricantes de Veículos Automotores (Anfavea)		March 10, 2012
Goldemberg	Jose	Universidade de Sao Paulo (USP); Formerly, Ministry of Science and Technology, Ministry of Education, and Ministry of Environment; Secretariat of Environment, State of Sao Paulo	**	November 16, 2010-March 18, 2012
Guardabassi	Patricia	Universidade de Sao Paulo (USP)		November 16, 2010
Job	Luis	Ministry of Agriculture	**	March 5, 2012-September 6, 2012
Joseph Jr.	Henry	VW Brazil	**	December 2, 2011-August 13, 2012
Lago	Andre Aranha	Ministério das Relações Exteriores		December 1, 2010

Individual		Institution		Dates
Leal	Manoel Regis	Laboratorio Nacional de Ciência e Tecnologia do Bioetanol (CTBE); Formerly Copersucar-CTC	**	November 18, 2010-August 30, 2012
Leite	Rogerio	Retired, Universidade de Campinas (UNICAMP)	**	August 15, 2012-August 16, 2012
Melo	Lucia	Center for Strategic Studies and Management in Science, Technology and Innovation (CGEE)		November 30, 2010
Milanez	Artur	Banco Nacional de Desenvolvimento Economico e Social (BNDES)		November 25, 2010
Moreira	Jose	Universidade de Sao Paulo and Centro Nacional de Referência em Biomassa (USP and CENBIO)	**	February 28, 2012-September 5, 2012
Moss	Hamilton	Ministerio de Minas e Energia (MME)		December 3, 2010
Netto	Antonio Delfim	Formerly, Ministry of Finance and Ministry of Planning, Budget, and Management		November 19, 2010
Nogueira	L.A. Horta	Universidade Federal de Itajubá	**	March 18, 2012-April 3, 2012
Pereira	Mario	PSR, Electricity and Natural Gas Consuting and Technical Services	**	November 10, 2010-February 13, 2012
Poppe	Marcelo	Center for Strategic Studies and Management in Science, Technology and Innovation (CGEE)		November 30, 2010
Rayol	Caroline	Análise e Acompanhamento de Políticas Governamentais, Planalto		November 29, 2010
Reis	Tereza	Energy Consulting		November 26, 2010
Rezende	Sergio	University Federal de Pernambuco; Formerly, Ministrio da Ciencia e Tecnologia	**	December 6 2010-June 29, 2012
Rodrigues	Rodrigo	Formerly, Ministry of Agriculture		July 5, 2012
Rodrigues	Rodrigo	Executive Interministerial Commission for Biodiesel, Planalto		November 29, 2010
Schaeffer	Roberto	Instituto Alberto Luiz Coimbra de Pos-Graduacao e Pesquisa de Engenharia (COPPE), UFRJ	**	November 23 2010-July 6, 2012
Seabra	Joaquim	Laboratorio Nacional de Ciência e Tecnologia do Bioetanol (CTBE)	**	November 18 2010-July 13, 2012
Soriano	Eduardo	Ministry of Science and Technology		December 6, 2010

Individual		Institution		Dates
Sousa	Bruna	Ministerio de Minas e Energia (MME)		December 6, 2010
Souza	Eduardo	Sugar Cane Industry Association (UNICA)		November 16, 2010
Szklo	Alexandre	Instituto Alberto Luiz Coimbra de Pos-Graduacao e Pesquisa de Engenharia (COPPE), UFRJ		June 29, 2012
Szwarc	Alfred	Sugar Cane Industry Association (UNICA)	**	November 16, 2010-August 13, 2012
Trein	Cristiano	Ministerio de Minas e Energia (MME)		December 6, 2010
Ueki	Shigeaki	Formerly, Ministry of Energy and Petrobras	**	November 23, 2010-June 28, 2012
Valesci	Octavio Antonio	Universidade Federal de São Carlos	**	January 5, 2011-May 31, 2012
Vieira	Jose Nilton	Undersecretariat, Government Programs and Actions, Office of the President; Formerly, Ministry of Agriculture	**	November 29, 2010-August 15, 2012

Interviews/Communications: Denmark

***Note: Multiple interviews/communications*

Individual		Institution		Dates
Albrechtsen	Karl	Danish Wind Secretariat/Sekretariatschef, Vindmøllesekretariatet	**	March 12, 2011-July 2012
Alexandersen	Peter	Danish Wind Industry Association	**	June 1, 2012-June 18, 2012
Andersen	Per	Technical University of Denmark	**	June 7, 2011-May 27, 2012
Bengtsson	Gitte	Regional Political Directorate, Danske Regioner		May 29, 2012
Christensen	Peter	Samsoe Island, Consulting		May 26, 2011
Gregersen	Brigitte	Aalborg University	**	May 24, 2011-April 25, 2012
Henningsen	Jorgen	Formerly, Directorate General Environment, EU-Commission		May 27, 2011
Hogh	Jakob	Danish Energy Association		May 1, 2011
Holmgaard	Per	Holmgaard Consulting; Formerly, Vestasa and DONG Energy	**	May 27, 2011-September 20, 2011
Hvelplund	Frede	Aalborg University Denmark	**	June 6-June 20, 2012
Johansen	Knud	Energinet TSO	**	June 9, 2011-June 6, 2012
Karnoe	Peter	Aalborg University	**	May 19, 2011-June 4, 2012
Krohn	Soren	Soren Krohn Consulting; World Bank; Formerly, Danish Wind Energy Association		May 23, 2012
Lemming	Jorgen	Technical University of Denmark (DTU)	**	June 5, 2012-June 25, 2012
Lenjas	Marika	Vestas		May 1, 2011
Lundvall	Bengt Ake	Aalborg University	**	May 24, 2011-April 24, 2012
Madsen	Birger	BTM Consulting/Navigant	**	May 23, 2011-August 13, 2012
Maegaard	Preben	Nordic Folkecenter for Renewable Energy		May 24, 2011
Meyer	Niels	Technical University of Denmak (DTU)	**	February 8, 2011-June 27, 2012
Naef	Stefan	Middelgrunden Wind Turbine Cooperative		May 18, 2011
Nielsen	Charles	DONG Energy		May 30, 2011
Nielson	Poul	Formerly, Ministry of Energy, Ministry for Development Cooperation	**	May 24, 2011-April 23, 2012
Ostergard	Klaus	Ringobing Landobank		May 31, 2012
Parbo	Henning	Energinet		September 1, 2011
Pedersen	Jorgen	Technical University of Denmak (DTU)	**	April 24, 2012-May 21, 2012
Sorenson	Erik	Vestas		May 16, 2011
Sorenson	Hans	Spok Aps, Middelgrunden, and Danish Wind Turbine Owners Association Board	**	May 18, 2011-May 23, 2011
Sperling	Karl	Aalborg University	**	June 18-June 20, 2012

Individual		Institution		Dates
Stensgaard	Soren	Samsoe Municipal Government		May 26, 2011
Stridbaek	Ulrik	Dong Energy		May 25, 2011
Thomassen	Bjarke	Poul la Cour Foundation and Museum	**	May 21, 2011-June 8, 2012
Vildbrad	Lars	Regional Development, Central Denmark Region	**	May 29, 2012-June 8, 2012

Interviews/Communications: France

***Note: Multiple interviews/communications*

Individual		Institution		Dates
Ailleret	Francois	Electricité de France/Electricity of France (EDF)		July 11, 2011
Bamberger	Yves	Electricité de France/Electricity of France (EDF)		February 14, 2011
Barre	Betrand	Nuclear Energy Academy (INEA) and European Nuclear Society (ENS)	**	July 4, 2011-August 21, 2012
Bensaude-Vincent	Bernadette	Université Paris X		July 1, 2011
Berest	Pierre	École Polytechnique	**	July 4, 2011-August 24, 2012
Boiteux	Marcel	Formerly, Electricité de France/Electricity of France (EDF)		February 10, 2011-March 4, 2011
Bouchard	Jacques	Formerly, Atomic Energy and Alternative Energies Commission (CEA)	**	July 7, 2011-June 7, 2012
Boulin	Philippe	Formerly, Framatome	**	July 5, 2011-November 7, 2011
Carre	Frank	Atomic Energy and Alternative Energies Commission (CEA)	**	March 10, 2011-July 25, 2012
Comby	Bruno	Environmentalists For Nuclear Energy	**	June 30, 2011-July 4, 2011
Figuet	Jacques	Nuclear Energy Counsel, Embassy of France, Washington DC	**	April 2011-August 28, 2012
Golay	Michael	Massachussetts Institute of Technology (MIT)		August 18, 2012
Gollion	Jacques	Retired, AREVA	**	June 24, 2011-July 27, 2012
Gozalo	Laurence	Formerly, Atomic Energy and Alternative Energies Commission (CEA) and French Nuclear Safety Authority (ANS)		October 13, 2010
Lavergne	Richard	Directorate General for Energy & Climate (DGEC), Ministere Ecologie, Energie, Developpement Durable et Mer		July 7, 2011-July 27, 2012
Leny	Jean-Claude	Formerly, Framatome		July 9, 20011
Mijeon	Charlotte	Sortir du Nucleaire		June 30, 2011
Nignon	Jean-Louise	Retired, AREVA	**	June 30, 2011-July 27, 2012
Ouzounian	Gerald	Agence Nationale Pour la Gestion des Déchets Radioactifs/National Agency for the Management of Radioactive Waste (ANDRA)	**	July 6, 2011-July 2012
Schneider	Mycle	Energy Consulting	**	July 23, 2012-July 25, 2012
Serpantie	Jean-Pol	AREVA	**	July 8, 2011-June 7, 2012
Thomas	Jean-Baptiste	Atomic Energy and Alternative Energies Commission (CEA)		July 5, 2011
Topcu	Sezin	Le Centre National de la Recherche Scientifique	**	July 8, 2011-August 5, 2012
Vidard	Michel	Electricité de France/Electricity of France (EDF)	**	July 6, 2011-October 30, 2011

Interviews/Communications: Iceland
***Note: Multiple interviews/communications*

Individual		Institution		Dates
Albertsson	Albert	HS Orka	**	July 22, 2011-August 8, 2012
Asbjornsson	Magnus	Reykjavik Geothermal		July 13, 2011
Bardadottir	Helga	Ministry of Industry, Energy and Tourism	**	July 12, 2011-July 10, 2012
Bjornsson	Sveinbjorn	Retired, National Energy Authority and Iceland University	**	July 13, 2011-August 28, 2012
Blondal	Karl	Morgunbladid Newspaper		July 25, 2012
Corgan	Michael	Boston University		July 12, 2012-August 17, 2012
Eyjolfsson	Eythor	Sure Step Iceland; Formerly, Fish Inspecting and Consulting		July 1, 2011
Finnsson	Arni	Icelandic Nature Conservancy	**	July 15, 2011-August 20, 2012
Flovenz	Olafur	Iceland Geosurvey/ISOR		August 1, 2012
Fridleifsson	Ingvar	United Nations Geothermal Training Programme		July 12, 2012
Gestdottir	Erla	Ministry of Industry, Energy and Tourism	**	July 12, 2011-August 16, 2012
Gislason	Gestur	Reykjavik Geothermal		July 13, 2011
Gunnarsson	Hakon	Gekon Cluster (Geothermal)		August 13, 2012
Hafliðason	Kristinn	Invest Iceland		August 1, 2010
Helgason	Thorkell	Formerly, National Energy Authority	**	July 23, 2012-August 13, 2012
Ingason	Kristinn	Mannvit		July 20, 2012
Ingimarsson	Jon	Landsvirkjun (National Power Company of Iceland)	**	July 14, 2011-July 26, 2012
Johannessson	Gudni	Orkustofnun / National Energy Authority	**	July 13, 2011-July 12, 2012
Jonasson	Thorgils	National Energy Authority of Iceland (NEA)		September 4, 2012
Jonatansson	Svavar	Formerly, Almenna	**	July 20, 2012-August 20, 2012
Jonsdottir	Rosa	National Energy Authority of Iceland (NEA)		August 20, 2012
Kettilsson	Jonas	Geothermal Development and Research, NEA	**	July 30, 2012-August 13, 2012
Magnason	Andri Snaer	Author, Documentary Film Maker		August 7, 2012
Olafsson	Hugi	Ministry for the Environment, Office of Policy and International Affairs	**	July 12, 2011-August 2012
Olafsson	Magnus	Iceland Geosurvey/ISOR		July 13, 2012
Pálsdóttir	Sigrún	Author and Editor - Saga Journal, Historical Society of Iceland		August 20, 2012
Richter	Alexander	Canadian Geothermal Energy Association; Formerly, Islandbanki	**	July 12, 2012-July 16, 2012
Saemundsson	Rognvaldur	Reykjavik University		July 7, 2011
Skulason	Gustaf	Samorka - Icelandic Energy and Utilities		August 1, 2012
Stadler	Christina	Agricultural University of Iceland		July 20, 2012
Svanbjornsson	Andres	Formerly, Markeing Office, Landsvirkjun-Ministry of Industry	**	July 1, 2012
Tester	Jeff	Cornell University		November 7, 2011
Þórarinsdóttir	Ragnheiður	Gekon Cluster (Geothermal)		August 1, 2012
Thorbjornsson	Ingolfur	Technological Development, Innovation Centre Iceland		July 10, 2012
Thoroddsson	Gudmundur	Reykjavik Geothermal	**	July 13, 2011-August 2012
Valfells	Agust	Reykjavik University		July 13, 2011
Valsson	Elvar	Ministry of Industry, Energy and Tourism	**	July 12, 2011-July 16, 2012